ELECTRICAL ILLUMINATING ENGINEERING.

BY

WILLIAM EDWARD BARROWS, JR., B.S., E.E.

Assistant Professor of Electrical Engineering, Armour Institute of Technology; Associate Member American Institute of Electrical Engineers, Member Illuminating Engineering Society, Member Society for the Promotion of Engineering Education.

NEW YORK

McGRAW PUBLISHING COMPANY

239 West 39th Street

1908

PREFACE.

This book had its origin in a set of notes compiled and developed by the author for use in his classes. At that time there was no thought of publishing the material and no record was made of the sources of information. However, the work of Professor Wilbur M. Stine on "Photometrical Measurements" was consulted freely and in that department of the subject will be found a valuable reference. Much of the material was obtained from the *Transactions* of the American Institute of Electrical Engineers, the *Proceedings* of the National Electric Light Association, and the *Transactions* of the Illuminating Engineering Society, as well as from the *Illuminating Engineer*, the *Electrical World*, the *Electrical Age*, the *Electrical Review*, *Science Abstracts*, and other technical periodicals. The absence of a satisfactory text in Illuminating Engineering and the hope that a book of this nature might be of service to the profession prompted the development of the work to its present condition.

Throughout the book there is little descriptive detail. The size of the book necessarily prohibits this and in the author's opinion such detail may more profitably be given by supplementary lectures, or may be obtained on the part of the student by close observation of prevailing practice, or by careful perusal of the contemporary technical press.

SEPTEMBER, 1908. W. E. B., JR.

CONTENTS.

Electrical Illuminating Engineering

CHAPTER I.

LIGHT AND COLOR.

The phenomenon of light is inherently the same as that of heat and other forms of energy although the vibratory or wave motion is of much higher frequency. The light waves are those having a frequency such that when received on the retina of the eye produce sight sensations. The frequency of the ether waves producing light ranges from 392×10^{12} per second, corresponding to the red extremity of the spectrum, to 760×10^{12} per second the outer limit of the violet end of the spectrum. The wave length of red light is approximately 7×10^{-4} millimeters while the pure violet wave is about 4×10^{-4} millimeters. The velocity of light has been found to be approximately 186,660 miles per second.

Rays of light falling on a surface are either reflected, absorbed, or transmitted depending on the nature of the substance of which the surface is composed. If the surface is smooth the reflected rays are specular and make an angle with a normal to the surface equal to the angle of incidence. If the surface is rough the reflected rays are diffused. By a proper choice and arrangement of the molecules of a substance, rays of a desired frequency may be reflected or transmitted and all others absorbed thus giving rise to the color of the body or of the transmitted rays. Substances differ greatly in their property of absorption and reflection and to this is due the variety of colors of objects. The amount of light reflected from a particular surface depends upon the angle of incidence and the molecular condition of the surface.

In general the amount of light reflected from surfaces of various colors in per cent. of the light received is given in the following table:

Nature of Surface	Per cent. Reflected	Nature of Surface	Per cent. Reflected
Mirror	95	Blue wall paper	25
Polished silver	90	Plain deal (dirty)	20
White paper	80	Yellow paint (dirty)	20
Silvered glass	80	Emerald green paper	18
Polished brass	70	Dark brown paper	13
Chrome yellow	60	Vermilion paper	12
Polished steel	60	Blue green paper	12
Orange paper	50	Cobalt blue paper	12
Plain deal (clean)	45	Macadam road	12
Yellow paper	40	Glossy black paper	5
Yellow paint (clean)	40	Ultra-marine blue paper	4
Light pink paper	35	Deep chocolate paper	4
Tracing cloth	30	Dead black surface	1

The amount of light absorbed by the globes and glassware used on lamps to prolong the life of the incandescent parts, to diffuse the light, or to transmit light of a desired color will be seen to vary from 5 to 95 per cent:

Clear glass	globes	absorb	from	5–12	per cent.
Light sand blast	"	"	"	10–20	"
Alabaster	"	"	"	10–20	"
Canary colored	"	"	"	15–20	"
Light blue alabaster	"	"	"	15–25	"
Heavy blue alabaster	"	"	"	15–30	"
Ribbed glass	"	"	"	15–30	"
Opaline glass	"	"	"	15–40	"
Ground glass	"	"	"	20–30	"
Medium opalescent	"	"	"	25–40	"
Heavy "	"	"	"	30–60	"
Flame glass	"	"	"	30–60	"
Signal green	"	"	"	80–90	"
Ruby glass	"	"	"	85–90	"
Cobalt blue	"	"	"	90–95	"

The subject of light and the eye will next be considered and the question may naturally arise as to whether the intensity of sensation bears any relation to the magnitude of its stimulus. The result of exhaustive experiments show that the differences in sensations vary as the logarithm of the ratio of the stimuli producing them. The smallest distinct change in the illumination of an object which the trained eye can distinguish is about one per cent. The maximum light intensity which the eye can withstand without bad effect is 4.25 candles per square inch and the greater the brightness or the greater the area of the source with the same intensity, the more the eye will be affected. Only paraffin candles, oil lamps, and special kinds of gas and kerosene lamps give a flame of intensity below this limit. Other sources of light should be equipped with diffractive globes. The intensities of some of the common sources of light in candle-power per square inch are given in the following table:

The Moore tube	0.6
Frosted incandescent lamp	2–5
Candle flame	3–4
Gas flame	3–8
Oil lamp	3–5
Kerosene lamp	4–8
Cooper Hewitt lamp	16.7
Welsbach gas mantle	20–25
Acetylene flame	75–100
Enclosed a.c. arc depending on globe	75–200
Enclosed d.c. arc depending on globe	100–500
Incandescent lamp, 4 watts per candle	300
Incandescent lamp, 3.5 watts per candle	375
Incandescent lamp, 3.1 watts per candle	480
Gem lamp, 2.5 watts per candle	625
Tantalum lamp, 2 watts per candle	750
Nernst lamp (bare)	800–1000
Tungsten lamp, 1.25 watts per candle	1000
Sun on the horizon	2000
Flaming arc	5000
Open arc lamp	10,000–50,000
Open arc crater	200,000
Sun 30° above the horizon	500,000
Sun at zenith	600,000

The part which the eye plays in protecting itself can be best understood from a brief description of its construction. It consists essentially of three parts—the iris, the focusing lens and the retina. The iris is a diaphragm which expands or contracts to regulate to a certain extent the amount of light, which, passing through the focusing lens, falls upon the retina at the back of the eye-ball, exciting the optic nerves which lead to the base of the brain. The nerves in the retina are known as the "rods" and "cones." At ordinary illumination the cones are active and they are most susceptible to yellow light, but when the illumination is reduced to such a point that the rods become the predominating organs, the blue and green become the most useful portion of the spectrum. The central portion of the retina is much less sensitive to the voilet end of the spectrum than the surrounding portion of the retina. The retina is the sensitive part of the eye and while it is wonderful in its ability to recuperate, it is by no means immune from injury; and this little member, the eye, should ever be in mind when considering the details of any illuminating system.

A peculiar psychological phenomenon occurs, through fatigue of the eye, after looking at a brightly illuminated body. If, for instance, after looking intently for some time at a red surface we turn our eyes to a white surface it will appear greenish blue. Also, if alternate strips of black and white be looked at closely the white will appear much brighter by contrast with the black, and a black body with a red background can be distinguished, as to detail, at a greater distance than if the background were green.

If repeated stimuli succeed each other within their period of persistence the sensation which they produce is that of continuous light, but when the interval between the stimuli is nearly equal to the time of dying away of a sensation the light will appear to flicker. A flickering light should be avoided, since the iris cannot keep pace with the rapid fluctuations, and too little and too much light falling alternately on the retina produces fatigue. This is familiar to all who have attempted to read by light from an open gas flame or a 25-cycle arc lamp. The frequency at which the flicker from an alternating current source cannot be detected varies with the intensity of illumination of the body viewed. This will be seen from the following data by Dr. Kennelly in which the source of light was an incandescent lamp having a mean horizontal intensity of 33.04 candle-power, placed at different distances from a screen and the screen viewed from a distance of 50 centimeters. The values given are the average results obtained by three observers.

Distance between lamp and screen in meters..	4.0	3.0	2.5	2.0	1.5	1.0	0.5
Meter-candles on screen.	2.065	3.67	5.29	8.26	14.69	33.04	132.2
Mean flicker-vanishing frequency............	25.6	27.4	29.3	32.0	35.2	36.8	44.1

In regard to illumination in general, a careful study should be made of the necessary and most satisfactory intensity and distribution of light concurrent with the general wellfare of the people for whose use the system is designed. Too little light is likely to cause a strain on the retina; while, on the other hand, too much light should be avoided since the contraction of the iris is limited and a strain will likewise be imposed upon the retina.

Luminous sources should be so placed that the rays, either direct or reflected, will not pass directly into the eye. The result of sources thus wrongly located is, that objects back of the source in the case of direct rays, and the reflecting medium if the rays are reflected, are more or less indistinct. Light coming from an unusual angle should be avoided. We receive our light usually from above and the retina becomes accustomed to light from that direction, while light reflected into the eye from below as from snow or the direct rays from footlights may not only cause fatigue but sometimes temporary blindness. Streaks of light and sharp contrasts are injurious to the eye, the effect being similar to that of a flickering light.

During all work with ultra-violet rays it is necessary to protect the eyes with suitable glasses since the ultra-violet rays cause flourescence in the eyes resulting in exhaustion of the nerves and alteration of the transparent network.

Experience shows that at one or two foot-candles the eye is working so near its normal condition that any further increase in illumination is of relatively small value. The values here specified are those affecting the eye and not those by which the objects are illuminated. This must necessarily be reflected light and, as the coefficients of reflection and diffusion vary over a wide range, the calculation of the amount of light required from the primary source is not a simple problem. However, if the class of service, for which artificial light is to be used, be known, the approximate intensity of the source of light required can be calculated from general physiological and physical data. The lowest permissible illumination is, of course, for work on light colored objects or where only the general outline of the objects is required while the highest illumination would be used for close discrimination of details on dark objects. A general idea of the intensity of light for some of the common classes of service can be obtained from the following table which represents values in foot-candles recommended for satisfactory illumination:

Assembly rooms, corridors, public spaces		0.5 – 1.5
Auditoriums, theatres		1.0 – 3.0
General illumination of residences		1.0 – 2.0
Reading	Good clear print	1.0 – 1.5
	News paper print	2.0 – 2.5
	Postal service	2.0 – 4.0
Churches		2.0 – 4.0
Library	General illumination	1.0 – 2.0
	Reading tables	3.0 4.0
Ball rooms		2.0 – 3.0
Desk lighting		2.0 – 5.0
General illumination of stores		2.0 – 5.0
Bookkeeping and clerical work		3.0 – 5.0
Clothing stores		4.0 – 7.0
Display of dark goods		5.0 –10.0
Drafting, engraving		5.0 –10.0
Street lighting by gas		0.05 – 0.25
Street lighting by electricity		0.05 – 0.60
Light from a full moon gives		0.025– 0.03

Color plays an important part in interior lighting and especially so in stores or shops where colored merchandise is displayed, in which cases the illumination should approximate as near as possible the color values of diffused daylight. In lighting a ballroom or an assembly hall, a soft light rich in orange or yellow rays is usually preferable. After considering the color of the various illuminants given in the following list, we will study the effect of their light on different colored objects.

Acetylene	Nearly white
Arc light (enclosed)	Bluish white to violet
Arc light (open)	White
Arc light (high voltage arc)	Purple
Candle	Orange yellow
Carbon filament (below voltage)	Orange to orange red
Carbon filament (normal-voltage)	Yellowish white
Flaming arc lamp	Yellowish orange
Gas light (open flame)	Pale orange to yellowish white
Metalized filament	Nearly white, slightly yellow
Kerosene lamp	Orange, slightly yellow
Nernst lamp	Very nearly white
Sky light	Bluish white
Sun (high in sky)	White.
Sun (near the horizon)	Orange red
Tantalum lamp	Nearly white
Tungsten lamp	Very nearly white
Magnetite arc lamp	Bluish white
Mercury lamp	Bluish green
Moore lamp	Yellow, white or pink
Welsbach mantle	Greenish white

Incandescent lamps give varying results depending on the degree of incandescence. When burning low the light resembles gas light in color, while if they are pushed far above their normal candle power they are very rich in violet rays and ultimately become white at which temperature they quickly burn out. The color of light from the flaming arc depends on the salts with which the electrodes are impregnated, and the color of the light from the Moore tube depends on the nature of the gas with which the tube is fed.

An excellent idea of the color properties of various illuminants can be obtained by matching the visible color of a given illuminant accurately by mixtures of the three primary colors, red, blue-violet, and green, and to determine the exact proportion of each constituent required to give the same hue. Such experiments by Abney gave the following results:

	Sunlight	Skylight	Arc light	Gas light
Red................	100	100	100	100
Green..............	193	256	203	95
Violet..............	228	760	250	27

The effect of selective absorption which so deceives the eye when colored objects are viewed by colored light shows the necessity of a careful consideration of the colors of artificial light. We have all noticed the effect of the light from a mercury vapor lamp on the appearance of colored objects. When viewed in the rays of a green lantern, greens, yellows, browns, and grays are nearly of the same color but of different shades. In the same light, pink looks red and red appears black. Practical illuminants, however, do not cause serious deceptions although gas and candle light will change the hue of delicate colors containing greenish blue, blue, or violet. The light from incandescent lamps resembles that from brilliant gas flame in effect while the light from arcs more closely resembles daylight. Colors matched in the light from an arc lamp may stand the test in daylight but prove faulty when viewed in the light from a gas or incandescent lamp. Moreover, shades of the same color are differently affected by artificial light. Colors seem to change in a dim light, but this is a purely physiological matter, the eye differing in its sensibility to different colors at different intensities, as previously explained.

The effect of colored light on various colors as given in the Standard Handbook may be seen on the following page.

Color of Incident Light and Results.

Original color	Red Light	Orange Light	Yellow Light	Green Light	Blue Light	Violet Light
Black	Purplish Black	Deep Maroon	Olive-yellow	Greenish-brown	Blue-black	Faint Violet-black
White	Red	Orange	Light Yellow	Green	Blue	Violet
Red	Intense Red	Scarlet	Orange	Brown	Violet	Reddish-violet
Orange	Orange-red	Intense Orange	Yellow-orange	Faint Greenish-yellow	Violet-brown	Light red
Yellow	Orange	Yellow-orange	Orange-yellow	Yellowish-green	Green	Brown, faintly red
Light Green	Reddish-gray	Yellow-green	Greenish-yellow	Intense green	Blue-green	Light purple
Deep green	Reddish-black	Rusty green	Yellowish-green	Deep Intense Green	Greenish-blue	Bluish-gray
Light Blue	Violet	Orange-gray	Yellowish-green	Green-blue	Vivid Blue	Violet Blue
Deep Blue	Violet-purple	Orange-gray	Green-slate	Blue-green	Intenser Blue	Bright blue violet
Indigo Blue	Purple, slightly violet	Orange-maroon	Dull-Orange-yellow	Dull Green	Dark Indigo Blue	Deep-blue-violet
Violet	Purple	Red-maroon	Yellow-maroon	Bluish-green-brown	Deep Bluish-violet	Deep violet

CHAPTER II.

UNITS OF ILLUMINATION AND PHOTOMETRY.

The units of illumination and photometry in vogue in this country are based on a system of units adopted at the International Congress of Electricians at Geneva in 1896.

This assembly accepted the **bougie** (candle) as the unit of illuminous intensity, which unit should be equal to the luminous intensity of five square millimeters of incandescent platinum at the point of solidification. This was intended to be one-twentieth of the Violle standard, which consisted of one square centimeter of platinum under the same conditions.

The unit of illumination intensity was termed the **lux** and was that light on a normal plane one meter away from a source of one bougie.

The **lumen** or unit of flux was that light on one square meter having a uniform intensity of one lux.

The **lumen-hour** or quantity was the product of unit flux by unit time.

The **bougie** per **square meter** was the term given to the unit of intrinsic brilliancy.

These units were modified somewhat and new terms and specifications, recommended and defined, by a Committee on Standards, appointed by the American Institute of Electrical Engineers. The report of this committee was accepted by the board of directors and published in the Transactions of July, 1907. The part of the report pertaining to light was as follows:

Candle-power. The luminous intensity of sources of light is expressed in candle-power. The unit of candle-power should be derived from the standards maintained by the National Bureau of Standards at Washington, D. C., which standard unit of candle-power equals 100/88 of the Hefner unit under Reichsanstalt standard conditions for the Hefner. In practical measurements seasoned and carefully standardized incandescent lamps are more reliable and accurate than the primary standard.

Lumen-candle.* The total flux of light from a source is equal to the mean spherical intensity multiplied by 4π. The unit of flux is called the lumen-candle. A lumen-candle is the $\frac{1}{4\pi}$ times the total flux of light emitted by a source having a mean spherical intensity of one candle-power.

Meter-candle.* The unit of illumination is the meter-candle. This is the normal illumination produced by one unit of candle-power at a distance of one meter.

a. **Foot-candle*** illumination is occasionally expressed in foot-candles. A foot-candle is the normal illumination produced by one unit of candle-power at a distance of one foot.

1 foot-candle equals 10.764 meter candles.

The **efficiency**† of **electric lamps** should be stated in terms of mean spherical candle-power per watt at lamp terminals.

a. Efficiency, Auxiliary Devices. In illuminants requiring auxiliary power-consuming devices outside of the luminous body, such as steadying resistances in constant potential arc lamps, a distinction should be made between the net efficiency of the luminous source and the gross efficiency of the lamp. This distinction should always be stated. The gross efficiency should include the power consumed in the auxiliary resistance, etc. The net efficiency should, however, include the power consumed in the controlling mechanism of the lamp itself.

---

*The order of the compound units— candle-lumen, candle-meter, and candle-foot as given in the original report is here reversed since their plurals are misleading and they seem less significant than lumen-candles, meter-candles and foot-candles.

†The term "efficiency" is not used here in its proper sense since we have no means of determining the energy equivalent of light. In practice, however, it is becoming well established as meaning the candle-power per watt when used with reference to electric lamps.

Comparison between such sources of light should be made on the basis of gross efficiency, since the power consumed in the auxiliary device is essential to the operation.

b. A **standard circuit voltage** of 110 volts, or a multiple thereof, may be assumed, except where expressly stated otherwise.

Watts per candle. The specific consumption of an electric lamp is its watts consumption per mean spherical candle-power. "Watts per candle" is the term used commercially in connection with incandescent lamps, and denotes, watts per mean horizontal candle-power.

Photometric tests in which the results are stated in candle-power should always be made at such a distance from the source of light that the latter may be regarded as practically a point. Where tests are made at shorter distances, as for example in the measurement of lamps with reflectors, the results should always be given as "apparent candle-power" at the distance employed, which distance should always be specifically stated.

Basis for comparison. Either the total flux of light in lumen-candles, or the mean spherical candle-power, should always be used as the basis for comparing various luminous sources with each other, unless there is a clear understanding or statement to the contrary.

Incandescent lamps, rating. It is customary to rate incandescent lamps on the basis of their mean horizontal candle-power; but in comparing incandescent lamps in which the relative distribution of luminous intensity differs, the comparison should be based on their total flux of light measured in lumens, or on their mean spherical candle-power.

The **spherical reduction-factor** of a lamp equals the mean spherical candle-power divided by the mean horizontal candle-power.

The **total flux** of light in lumen-candles emitted by a lamp equals 4π multiplied by the mean horizontal candle-power multiplied by the spherical reduction-factor.

The **spherical reduction-factor** should only be used when properly determined for the particular type and characteristics of each lamp. The spherical reduction-factor permits of substantially accurate comparisons being made between the mean spherical candle-power of different types of lamps, and may be used in absence of proper facilities for direct measurements of mean spherical intensity.

Reading distance. Where standard photometric measurements are impracticable, approximate measurements of illuminants such as street lamps may be made by comparing their "reading distances" *i.e.*, by determining alternately the distances at which an ordinary size of reading print can just be read, by the same person or persons, when all other light is screened. The angle below the horizontal at which the measurement is made should be specified when it exceeds 15 degrees.

In **comparing different luminous sources** not only should their candle-power be compared, but also their relative form, intrinsic brilliancy, distribution of illumination, and character of light.

CHAPTER III.

PHOTOMETRY AND PHOTOMETERS.

For measuring the illuminating power of any source of light the standard of light is the fundamental feature and its importance is so great that it demands a considerable discussion and will be considered later. Having a reliable light standard the next important feature is the photometer. A photometer compares illumination intensities. The illumination, varying inversely as the square of the distance from the source, is made equal to that from some source of known candle-power. Then, from the law of inverse squares,

$$I_x = I_s \frac{l_x^2}{l_s^2}$$

where I_x and I_s are the candle-powers, and l_x and l_s are the distances from the screen of the unknown source and the known source, respectively.

The photometer in all its modifications consists of a screen and its accessories. The screen either reflects or diffuses the illuminations under comparison and may be observed directly by the eye unaided, or through the agency of some optical train. The light reflected by the screen is always less than the illumination which it receives and may or may not be of the same quality. Selective absorption is often utilized whereby reflected light from an appropriately colored surface agrees in color with the compared light. The sensitiveness of the apparatus increases with the reflecting power of the screen. Diffusing screens scatter the light in its transmission through them. They consist of some translucent substance and like the reflecting screens reduce the intensity of the light and may be designed to change its quality by selective absorption.

The relative luminosities of various colors are important considerations in illumination and not only do these vary for different colors but they are greatly affected by the intensity of the illumination as well—a fact curious in itself and very troublesome in photometry. The sensitiveness of a screen depends on its luminous efficiency. The sensitiveness of a photometer depends on the least amount of change in light which the observer is able to detect. This amount may vary from one part in 60 for a weak light to one part in 120 for a bright light.

Photometers may be classified in two general types; first, those dependent on visual acuity and known as **illuminometers,** which measure the light by the ability of the eye to detect objects illuminated by it; and, secondly, those in which the light to be measured is compared with that of a known source, the reliability of this class being based on the ability of the eye to judge equality of illumination. Devices of the former class are unsuitable for accurate work since they involve personal psychological factors, and errors are introduced due to the " Purkinje effect " which is most marked at such low intensities as are employed. Only photometers of the second class can be relied upon to yield reliable results. These instruments employ a photometric device, a standard source of light, a means of varying the intensity upon the photometric device, and a reflecting screen or a translucent plate for receiving the light to be measured. The photometric devices may be further divided into three groups; First, in order of invention, are those in which the two light sources illuminate adjacent fields having a well defined separating line, as in the Bouger and Ritche photometers. This group, although simple and inexpensive, lack sensibility and ease of manipulation. Second, those having screens with parts translucent and illuminated on one side by the comparison lamp and on the other by the unknown source, the two sides being presented in the field of vision as adjacent surfaces by means of mirrors or prisms. The Bunsen photometer is a well known representative of this group. The third group, of which the Lummer-Brodhun photometer is the principal type, consists of a set of prisms through which the illumination due to the two sources can be viewed in one field. Such devices possess the greater sensibility and ease in manipulation but are expensive and difficult of construction. For comparing low intensities they are superior to the others and are applicable, with fair sensibility, to the measurement of illumination intensities quite below the range of the other devices.

The intensity of the light which is admitted to the photometrical device, from either source, may be varied by means of absorbing media, dispersion lenses, polarization, variable diaphragms, rotating disks, inclination of the illuminated surface, and by varying the distances of the sources from the screen. This latter method is the most universally applicable, it possesses accuracy, reliability, simplicity, flexibility, and can be easily verified. Absorbing media offers a very satisfactory and practical means of decreasing illumination intensity, if it be free from selective absorption.

The plate or screen which receives the illumination should have a plain white surface to give as high sensibility as possible, and should possess high diffusing quality so that the intensity when viewed from an angle, will obey the cosine law. It should not introduce color errors due to selective absorption, nor be placed where either the instrument or the observer will intercept any of the light rays; furthermore it should be so designed that it can be placed at any angle in the vertical plane.

From the preceding paragraphs it will be seen that the ideal photometer should possess a test plate of plain white diffusing substance, the most reliable comparison source of light, the best means of varying the intensity of light admitted to the comparison device, and a photometric device of highest sensibility. For taking light surveys and for measuring illumination in general, portability and convenience of manipulation become of vital importance.

The **Bouguer photometer** is said to be the oldest form of apparatus for comparing illuminating sources. It consists of an opaque reflecting screen with a blackened partition normal to its plane at its center. The two sources of light are placed, one on either side of the partition and their distance from the screen adjusted until the illumination of the screen is the same on both sides of the partition.

Later **Potter** substituted a translucent screen in place of the opaque one, which enabled the observer to place the screen between himself and the sources of light.

The **Rumford** or **shadow photometer** consists of a white screen with a small rod in front of it. The sources are then placed at distances from the screen such that the shadows due to each lamp are of the same density.

The **Ritchie photometer** has its light sources placed in fixed positions at opposite ends of the bar. Mirrors, placed 45 degrees to the common axis of the sources, throws the light from each lamp on a comparing screen supplied with a blackened partition separating the rays from the two sources. The screen and mirrors are movable and since the screen is viewed from a point normal to the photometric axis the photometer can be enclosed in a compact sight box.

The **Bunsen photometer** is one of the oldest and simplest forms of photometers, moreover, it is still one of the most widely used and most generally efficient means of comparing the intensity of luminous sources. The arrangement is similar to the Ritchie. The screen is movable and is placed in the photometric axis. In its simplest form this screen consists of a sheet of white paper made transparent with paraffin or some other similar substance. The transparent portion is circular or star shaped and its edges sharply defined. The light falling on either side of the screen is partly reflected from the white part of the screen and a portion passes through the translucent spot. When the illumination on both sides of the screen is the same an equal amount of light is transmitted through the spot in each direction and if the light from each source is of the same hue the transparent portion of the screen should appear identical to the untreated part. Both sides of the screen are viewed simultaneously by means of two mirrors properly arranged. It is essential that the mirrors have the same reflecting power and make the same angle with the screen. Either or both sides of the screen can be used to obtain a balance and, the screen and mirrors being reversible, a second balance can be obtained and the mean taken as the result. The arrangement above described can be better understood from Fig. 1 where *o* is the eyepiece through which both sides of the screen *s c* are viewed by means of the mirrors *m m*.

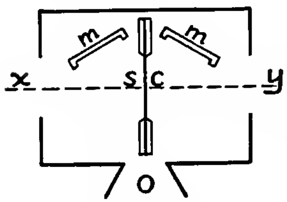


FIG. 1.

The **Lummer-Brodhun photometer** consists of a purely

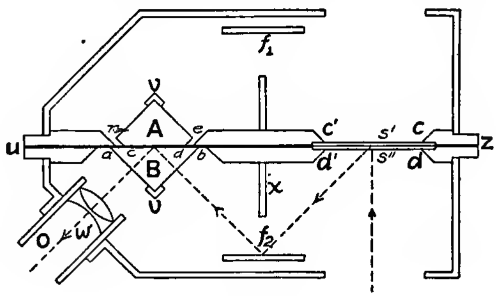


FIG. 2.

optical combination instead of the photometrical "grease spot" of the Bunsen photometer. A diffusing screen *s' s''* (Fig. 2) of high reflecting power is placed in, and with its plane normal to, the photometric axis. This screen is viewed on both sides by means of the optical device which presents both sides of the screen to the eye as adjacent fields.

The diffused light, reflected from the sides of the screen s' and s'', falls on the mirrors f_1 and f_2 and is reflected along the normal to the surface of the triangular prisms A and B. The observer, looking through the telescopic tube o directed normally to B clearly views the interior surface $a\ c\ d\ b$ of the prism B. The light from f_2 will be totally reflected to o from the portion of the surface $b\ d$ and $a\ c$, while that falling on $c\ d$ will be transmitted through A. and will not appear in the field to be compared. That portion of the light from f_1 which falls on $c\ d$ will be transmitted through B to o while the light falling on the parts $n\ c$ and $d\ e$ will likewise be reflected out of the field of vision. The observer will then view a three part field, the central part being illuminated by light from f_1; while the other portions receive light reflected by the mirror f_2. For the adjustment of the optical train and more details concerning this or the preceding types of photometers see Stine's "Photometrical Measurements."

The **Leonard Weber photometer** is especially adapted for the measurement of the intensity of illumination. It consists of a tube about 30 centimeters long (Fig. 3) supported on an upright rod so that it can be raised or lowered or turned in any desired direction. The standard source of light is contained in a lantern fastened to one end of the tube A. Within this tube is a circular piece of glass which can be moved lengthwise of the tube and its position read on a scale. At right angles to this tube, and supported at the end of the tube opposite the lantern, is a second tube B which can be rotated in a vertical plane, and its position relative to the vertical can be read on a graduated circle. A photometric train of the Lummer-Brodhun type which is contained in the tube B in its axis of rotation, receives light from the opal glass plate in tube A and reflects this light toward the eyepiece o in the tube B, so that the outer portion of the field of vision is illuminated by light from the standard source. The central zone of the field receives light from the source to be measured, through the prism p and the tube k. The intensity of this light can be decreased by means of one or more opal plates placed at *g* in order to make it comparable with that from the standard lamp. The tube *B* in making measurements is turned toward the light to be measured and it differs not whether the light be direct or reflected and diffused. A white screen of rough finish is usually used in connection with this apparatus and it can be set up at any desired inclination to the source of light. The

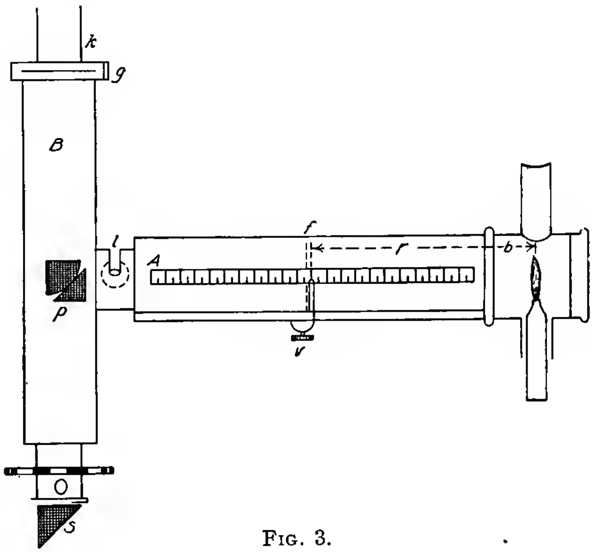


Fig. 3.

photometer may be placed at any convenient position and the tube *B* directed toward the center of the screen, the only restriction being that the field of vision receive no rays other than those emanating from the screen. The opal glass plate in tube *A* is now moved until both the central and the outer portions of the field of vision appear equally luminous. The distance *r* of this plate from the standard source of light, at the time of equal illumination on the comparison screen, is read on the scale in millimeters and the intensity of light on the screen calculated from the formula

$$I = K R^2/r^2$$

where R is the distance of the light from the screen and K is the constant previously determined as follows:—A standard candle is placed exactly one meter distant from the white screen and the tube B pointed toward its center and so placed that the eye perceives nothing but the light coming from the screen. The light intensity on the screen will then be one meter-candle and having obtained a balance the constant can be easily calculated. If other distances or standards are taken the difference must be taken into consideration. The photometer can be taken apart and packed in a small box 24 x 12 x 6 inches, which recommends it as a portable piece of apparatus and as such a miniature incandescent lamp is found very satis-

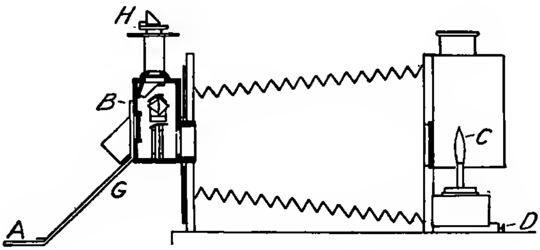


FIG. 4.

factory as a standard; it should, however, be calibrated before and after each test.

The Weber photometer is now made in a more portable form and with some modifications as shown in Fig. 4. The screen is fixed relative to the photometric device, but may be placed at any angle in a vertical plane, the photometric device moving with it around the horizontal axis of the comparison lamp. A photometric balance is obtained by moving the standard lamp along the photometric axis. This photometer is designed to employ the Hefner lamp as a standard. The results indicated by the position of the standard lamp when a balance is obtained, is in terms of a unit of illumination intensity. The range is increased by the use of absorbing screens.

Another modification of the Weber photometer known as the **Beckstein form** is shown in Fig. 5. A translucent plate *A* receives the light to be measured and is viewed through the optical device *H* and the prism *B*. The comparison lamp *C* is a benzine lamp in this case. The photometric balance is obtained by moving the translucent plate *G* along the photometric axis, the light transmitted by this plate is reflected by the prism *F* and is received at the eyepiece through the prisms *B*. This photometer may be calibrated similar to the Weber and its range can be extended by increasing the density of the plate at *A*.

The **universal photometer** represents the efforts of

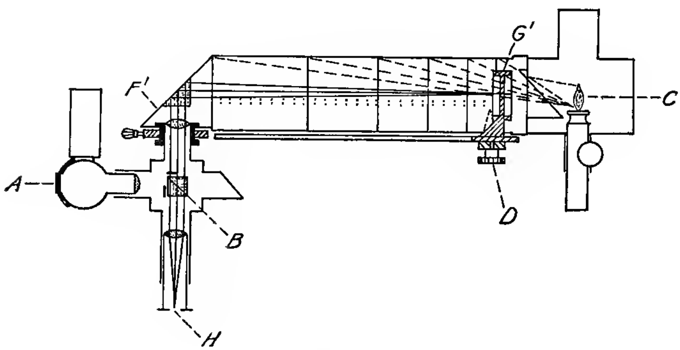


Fig. 5.

Messrs. Sharp and Millar in an endeavor to obtain an instrument of high sensibility and wide adaptability. In this photometer the optical device *B* is of the Lummer-Brodhun type with its sensitiveness increased by the addition of reflecting surfaces. The standard *C* is an incandescent lamp which is moved along the photometric axis by turning a knob *O*. This standard may be either a battery lamp, where constancy is desired, or a lamp to receive energy direct from lighting mains which, it is obvious, will be advantageous in measuring the candle-power of incandescent lamps. The illumination produced on the photometric device by the standard is made to vary inversely as the distance by means of automatically operating screens *G* which shield the device from reflected light. The instrument is calibrated to read in candle-power and foot-candles, the scale ranging from 0.4 to 20 foot-candles.

In the elbow of the tube *F*, which can be rotated around a horizontal axis and which is attached to the end of the box opposite the comparison lamp, is placed a 45-degree mirror. When it is desired to know the illumination intensity at any location, the end of this tube is equipped with a translucent plate *A* which is free from selective absorption and of good diffusing properties. The lower

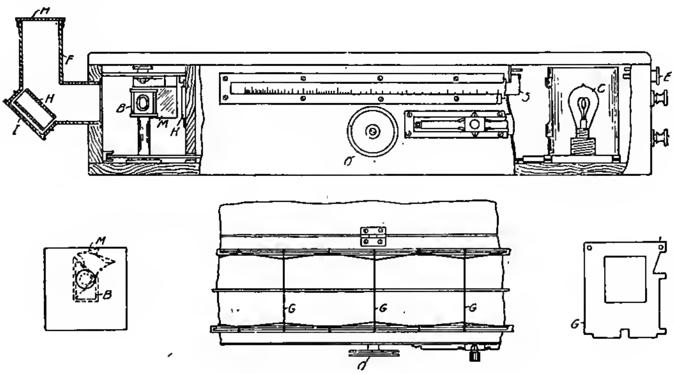


FIG. 6.

half of this plate is viewed through the eyepiece, by means of the prisms and the 45-degree mirror. The construction of this piece of apparatus can be understood from Fig. 6. The other half of the field of vision receives light through the prisms and a second translucent plate, *K*, from the comparison lamp. Photometric balance occurs when the plates *A* and *K* are illuminated to the same intensity.

When it is desired to measure the direct illumination from any source, the plate *A* is replaced by a screen having an opening through which the direct rays pass and fall upon a diffusing and reflecting surface *I* which has been substituted for the mirror. Photometric balance is obtained by comparing the brightness of the surface *I* and the plate *K*.

If the illumination intensity of any surface is to be measured, the mirror is placed at the elbow of the tube and the tube directed at the surface, the illumination of which it is desired to know. The comparison is then made directly between this surface and the plate *K*.

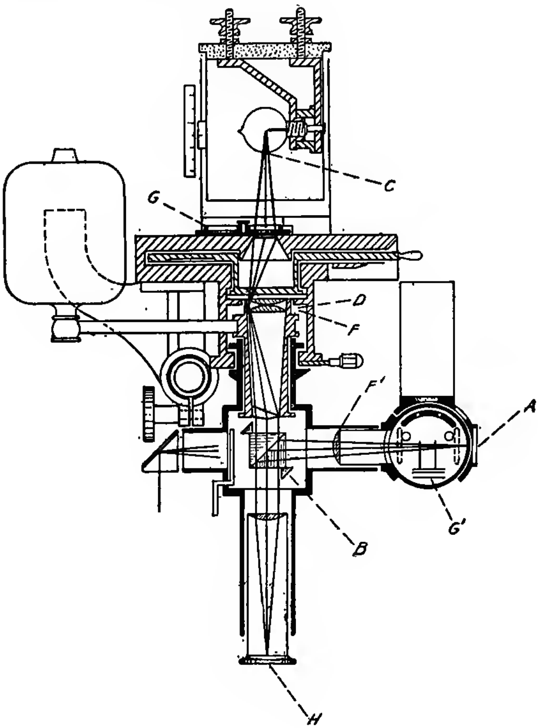


Fig. 7.

The range of this instrument can be increased by the use of absorbing screens or comparison lamps of different candle-powers.

It is claimed that this photometer can be used successfully for measuring the candle-power of incandescent, arc, or gas lamps either in the streets or laboratory; daylight illumination; interior illumination; and the intensity of illuminated surfaces.

In the following paragraphs will be found brief description of some of the recent types of portable photometers described by Mr. Millar in the Transactions of the Illuminating Engineering of October, 1907. The cuts are lettered similarly in order to facilitate comparison. "*A*" indicates the test plate, "*B*" the photometric device, "*C*" the comparison lamp, and "*D*" the means of varying the intensity of light on the photometric device.

The **sector type photometer**, designed by Walter Beckstein, is shown in Fig. 7. The test plate, *A*, is placed at the point where it is desired to study the illumination. This plate can be rotated throughout a vertical plane about

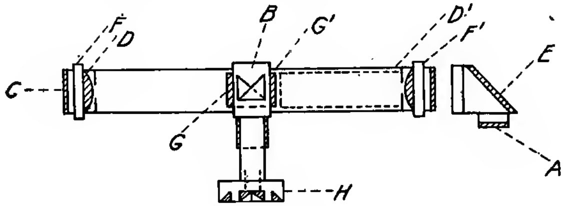


FIG. 8.

the photometric axis. *B* is a Lummer-Brodhun cube through which the lower surface of the test plate, *A*, is viewed. Through the prisms, *B*, may be viewed also the translucent plate *G*, which is illuminated by the comparison lamp, *C*. Equality of illumination is obtained by varying the size of the opening in the variable sector disk, *D*, and is determined by viewing the plate, *G*, through a portion of the lenses, *F*, which can be rotated. The result of the photometric setting is indicated by the size of the opening in the disk, *D*. This device is in effect, a rotating sector disk except that the beam of light, instead of the disk, is rotated, thus facilitating precise adjustment of the sector disk.

The **Blondel** and **Broca photometer** is shown in Fig. 8. That portion of the light which is transmitted through the test plate, *A*, is reflected from the 45-degree mirror, *E′*, through the lens *F′*, upon the ground glass plate, *G*, which forms part of the photometric device. Before the lens, *F′*, is placed a "cats-eye" diaphragm, *D′*. A comparison light source, *C*, which is not described, is placed to the left of the apparatus. The light passes through the lens, *F*, and falls upon the ground glass plate, *G*. A second adjustable "cats-eye" diaphragm, *D*, is placed before the lens, *F*. The photometric device, *B*, consists of crossed prisms through which the ground glass plates, *G* and *G′*,

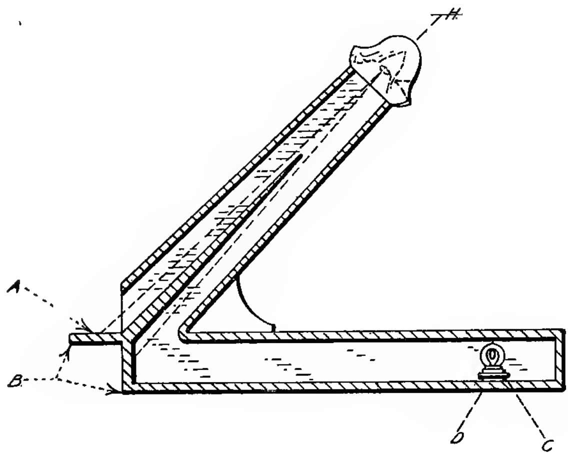


FIG. 9.

are viewed, from the binocular arrangement, *H*. Equality of illumination is produced by the adjustment of the diaphragms, *D* and *D′*, which are equipped with means for indicating the size of the aperture.

A vertical section of the **Burnett photometer** is shown in Fig. 9. The light to be studied falls upon a test plate, *A*, which is one surface of a photometric wedge. The other surface of the wedge is illuminated by the comparison lamp, *C*, which can be moved along the horizontal axis of the box. The two surfaces of the wedge which constitute the photometric device, *B*, are viewed from the position, *H*, through a box, divided by a partition which constitutes a well-defined line of separation between the two illuminated surfaces of the wedge. The results are indicated on a scale on the horizontal box which is calibrated directly in foot-candles.

In Fig. 10 is shown the arrangement of the **Marshall "illuminometer."** The test plate, *A*, is also the upper surface of the photometric device, *B*. This consists of a screen, the translucency of which is varied by using different thicknesses of paper. It is illuminated from beneath by the comparison electric lamp, *C*, the intensity of whose

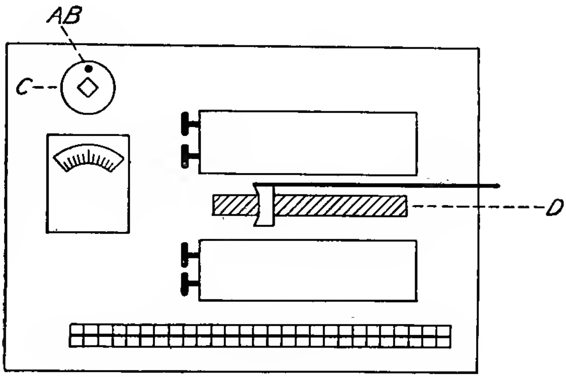


FIG. 10.

light is varied by means of the rheostat, *D*. The lamp, *C*, is operated from two dry cells within the instrument, a spring switch being placed in the circuit so that the cells are in use for a minimum time only. To effect a photometric setting, the amount of current through the lamp, *C*, is varied until disappearance of contrast is obtained at the screen, *B*, when viewed from above at an angle of about 45 degrees to its surface. The resistance of the lamp circuit is then measured by means of a simple Wheatstone bridge with a portable galvanometer, both inclosed within the instrument. One arm of this bridge consists of a tightly drawn resistance wire, supported over a millimeter scale. The contact is moved along this exposed wire until the point of no deflection is obtained and the foot-candle value then calculated from the scale reading by means of an interpretation curve.

Fig. 11 shows a vertical section through the **Martens photometer.** *A*, which receives the light to be studied, is observed through the photometric device, *B*, through

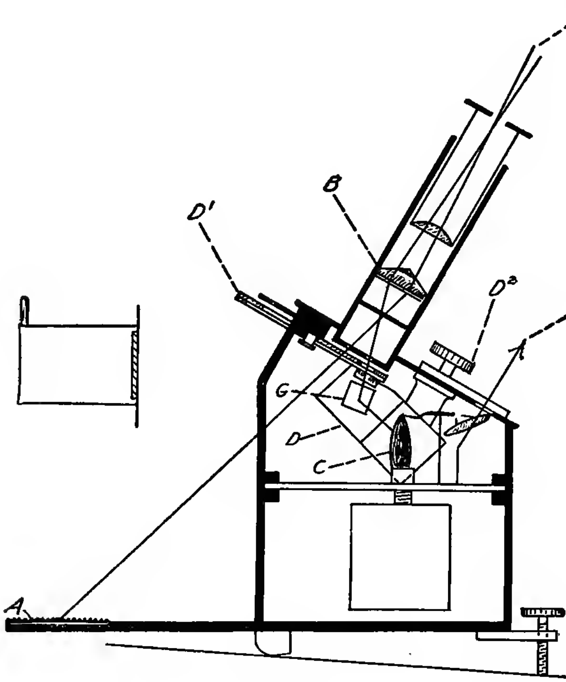


FIG 11.

which may also be seen the surface of the plate, *G*, which is illuminated by the comparison benzine lamp, *C*, through a pair of sliding mirrors, *D*. These mirrors vary the distance between the lamp, *C*, and the plate, *G*, being operated by the rack and pinion device, D^2. Results are read directly from a scale over which passes a pointer attached to D^2.

In the **Mascart's photometer,** shown in Fig. 12, the light to be studied falls on the translucent screen, A, which constitutes the test plate. That which is transmitted passes through the 45-degree mirror, E', a convex lens, and falls upon the upper half of the translucent screen, B. A comparison lamp, C, illuminates translucent screen, G. Light which is transmitted through this screen passes through a convex lens, the 45-degree mirror, E, the totally reflecting prism immediately above E, and falls upon the lower part of the screen B, where it is viewed from position H. Both of the lenses just mentioned have adjustable diaphragms, D and D', which are used to vary the intensity and effect equality of illumination upon screen B. The adjustment of these diaphragms indicates the result of the photometric settings. The comparison lamp, C, is a flat flame

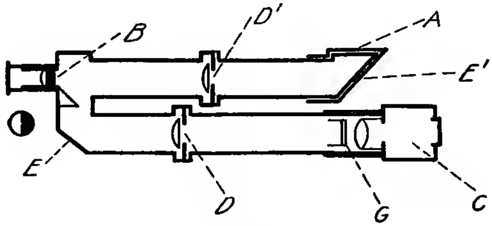


FIG. 12.

gasoline lamp. The instrument is calibrated by means of a Carcel lamp, whose light falls upon the test plate, A.

The **Preece and Trotter photometer,** of which a vertical section is shown in Fig. 13, has a test plate, A, upon which the light to be studied, falls and which is also a portion of the photometric device, B. The comparison lamp, C, illuminates a piece of bristol board, D, which may be inclined at any desired angle. Through slits in the surface, A, portions of the screen, D, may be viewed. Photometric balance is obtained by equalizing the brightness of the surfaces, A and D. I consists of a mirror and gage for adjusting the height of the flame of the lamp, C.

In **Ryan's photometer,** Fig. 14, the light to be compared falls at A upon one surface of the photometric device, B, which consists of a translucent block, diagonally divided by a thin, opaque film. The comparison lamp, *C*, illuminates the other half of the block. The distance between this lamp and the block is varied by means of the

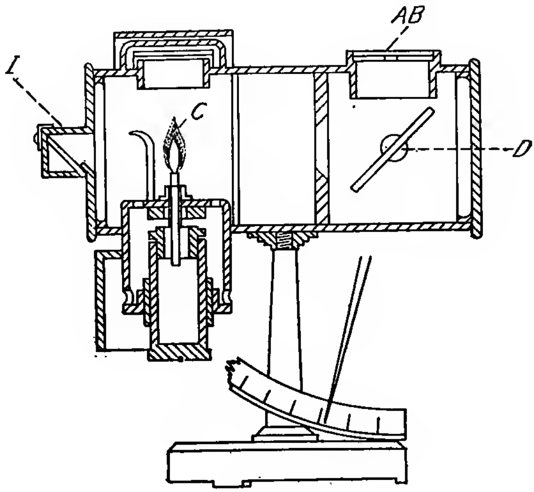


FIG. 13.

rod, *D*, upon which is calibrated a scale which indicates the results of the photometric settings. The photometric device, *B*, is viewed through the side, equal portions of the two halves of the block being present in the field of vision.

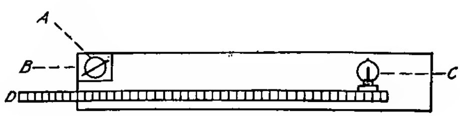


FIG. 14.

The **flicker photometer.** As illumination grows very bright, all colored objects incline toward a whitish yellow tint, which must gradually modify the quality of the sensation appropriate to that particular color of light. A red surface appears brighter than a blue one in daylight while the reverse occurs if these surfaces are viewed in weak daylight, when red may appear black while the blue will still be visible in its proper color. In a bright light, red, orange, and yellow surfaces are relatively more brightly illuminated than blue or violet surfaces, while just the opposite relations occur in a weak light. This is called the Purkinje effect and must be guarded against in photometry, since an arc lamp when compared with an incandescent will appear to an advantage when the lamps are a considerable distance apart and the photometer screen weakly illuminated, while the photometer setting will favor the incandescent lamp if the screen is brightly illuminated.

The flicker photometer has been designed for comparing dissimilar lights by presenting to the eye, surfaces illuminated by each light source in rapidly alternating succession. Perhaps the only logical basis of comparison is that lights differing in color shall produce equally intense sensations of luminosity for viewing fine lines or print, but as this involves all the psychological and physical difficulties already discussed, the results would be unsatisfactory, and the flicker photometer offers the most successful means of effecting this comparison. This photometer is made in a number of different forms. It may consist of one of the preceding types of photometers with a sector rotating before each lamp and so adjusted as to eclipse each light in succession, or it may have a distinct design of its own. One type of the flicker photometer consists of a concave cylindrical lens mounted on the top of an oscillating bar and placed between the observing tube and the prismatic screen which receives the light. Another form of this type of potometer consists of a revolving white disk with each half of its circumference beveled to 45 degrees in opposite directions so as to present the light from each source in succession.

The rapid alternations of illumination and eclipse of the screen tend to exercise the eye at its maximum sensitiveness and for this reason should reduce the personal variable between observers. It has been found that a frequency of 16 alternations per second will produce the condition of maximum sensitiveness.

The results of tests show that this type of apparatus can be used for comparing light sources, presenting the widest contrast in color, with an accuracy approaching that of the ordinary types of photometers when balancing lights of the same color. Such results are obtainable only with the normal eye, the fatigued eye showing a differential sensibility toward one of the lights. In general this apparatus requires a strong illumination of the screen in order to operate effectively, a fact which under ordinary conditions would favor the light possessing the more red rays.

The **Selenium photometer** takes advantage of the fact that the electrical condition of selenium changes under the influence of light. This property of selenium makes it especially fit for the construction of photometers, although nearly all attempts to construct a practical instrument have failed to yield satisfactory results. The disturbing influences are mainly the moisture and heat of the air and a gradual alteration in the condition of the selenium itself. One serious objection to this photometer is the long time it takes the resistance to assume a value corresponding to a given illumination. This is particularly true of the decrease of resistance.

The most successful selenium photometer is of German make. It consists of a device for exposing the cell alternately to the light from the standard and the source to be measured. The resulting current oscillations are detected by suitable instruments.

The setting is obtained by moving the photometer along the photometric axis until the instrument indicates a steady current.

Selenium seems to agree favorably with the luminous sensitiveness of the eye in respect to the illuminating value of lights of different colors.

The **bolometer** consists essentially of a very thin wire, usually of iron coated with carbon. When exposed to the light it becomes heated, and the change in its electrical resistance affords a means for measuring the energy intensity of the light rays. The bolometer is apt to indicate the heat rays rather than the illuminous rays.

Numerous attempts have been made to develop a **chemical photometer** but since the chemical action of the light is largely due to the ultra-violet or actinic rays, no success of any particular value has so far been achieved in this line.

CHAPTER IV.

SPHERICAL PHOTOMETRY AND INTEGRATING PHOTOMETERS.

For purpose of comparison or otherwise, it is often desirable to know the value of the mean spherical candle-power of a lamp. To determine the total amount of light emitted from a source which does not have a uniform distribution is not a simple matter. The distribution of light from an incandescent lamp is outward and downward as the lamp hangs suspended and it is a function of the cross-section of the filament and the form of the loop. In the direct current arc lamp, the greatest intensity of light is in a direction making an angle of 45 degrees with the horizontal, while the light from an alternating current arc has its greatest intensity in the horizontal plane.

One of the common methods of obtaining the mean spherical or the mean hemispherical candle-power of a lamp is by means of the Rousseau diagram. To accomplish this, the candle-power at a number of angles around the lamp in a vertical plane is measured, and the values, thus obtained, are plotted to scale on polar cross-section paper. This curve shows the distribution of light in a vertical plane. If, now, we assume the light to be surrounded by a sphere with the source of light as a center, and further consider this sphere divided into a number of zones in such a way that the illumination of similar parts of each zone is uniform, the total light embraced by a zone will be practically equal to the product of the average intensity and the area. From a summation of these products for each zone, the total volume of light from the source may be obtained, and this divided by the area of the sphere ($4\pi r^2$) will give the mean spherical candle-power. To obtain the lower hemispherical candle-power, the sum of the products of the zones and their intensities for the lower hemisphere is divided by the hemispherical area ($2\pi r^2$). These results are, it should be understood, only approximately correct. It can be shown that the area of the zones of a sphere are to each other as their altitudes, consequently, if the intensities be multiplied by the altitudes of the respective zones and the summation of the results be divided by the total value of the altitudes, the results above mentioned can be more easily obtained.

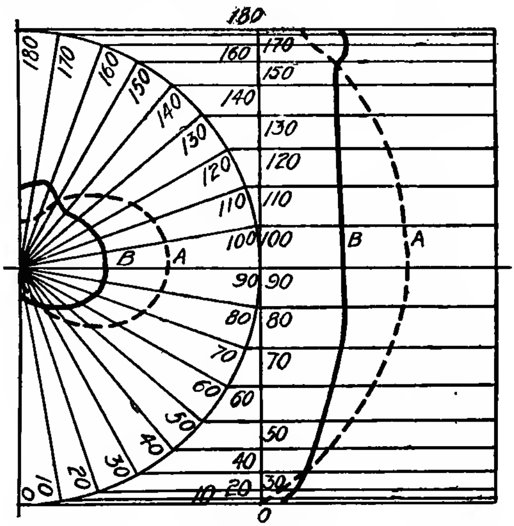


FIG. 15.

Advantage is taken of this proportionality in the **Rousseau diagram** method in which the results are arrived at graphically. The construction of this diagram is shown in Fig. 15. The values on the vertical axis are equal to the altitudes of zones subtended by angles of 10 degrees. If, at these points, the corresponding candle-powers be plotted as abscissæ, the area enclosed by a curve determined by these values and the vertical axis will be proportional to the illuminating power of the lamp, and the proportion of light in any zone will be clearly shown.

The curves shown in the figure are the distribution, *A*, of a bare Welsbach gas mantle and, *B*, the same mantle equipped with a plain opal glass egg-shaped globe. The values obtained from these curves are as follows:—

Curve A.	
Area above the horizontal axis	12.40 units
Area below the horizontal axis	10.78 units
Mean spherical candle-power	46.36
Curve B.	
Area above the horizontal axis	8.68 units
Area below the horizontal axis	7.21 units
Mean spherical candle-power	31.78
Efficiency of plain opal glass globe	68.5 per cent.

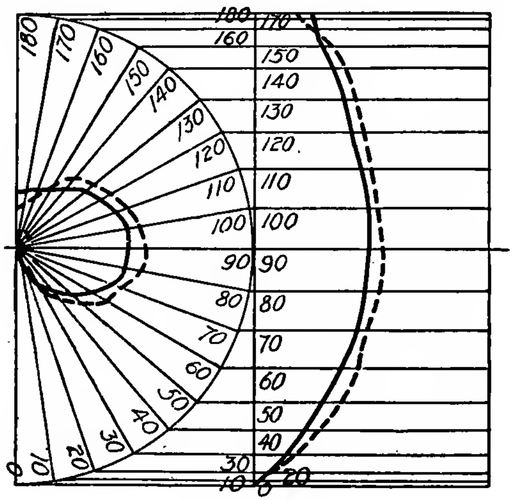


FIG. 16.

Fig. 16 shows the effect of a slightly opal glass egg-shaped globe. In this case the mean spherical candle-power without globe is 41.2; mean spherical candle-power with globe is 37.2. The efficiency of slightly opal glass globe is 90.2 per cent. It will be interesting to compare the effect of absorption given above with those tabulated on page 2.

Dr. A. E. Kennelly has devised a graphical construction for determining the spherical candle-power and the spherical reduction factor of a lamp, which requires only a pair of compasses and an angle protractor for application to the polar curve, and which is more nearly accurate under practical conditions of planimetry. The manipulation and theory of this method as given by Dr. Kennelly in the Transactions of the Illuminating Engineering Society is substantially as follows:

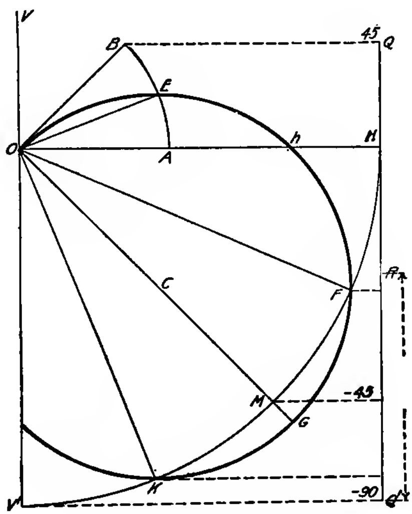


FIG. 17.

This diagram can, perhaps, best be explained by referring to an actual example, Fig. 17. The curve $O\,E\,F\,G\,K\,L$ represents the polar distribution curve of a particular luminous source occupying the virtual point O. This curve has been taken as a segment of a circle, with diameter $O\,G$ taken as unity, and depressed 45° below the horizontal plane $O\,H$. The reason for selecting such a circular polar curve is that its mean spherical intensity is easily computed. It follows from the computation that the mean spherical intensity of this polar curve, assumed as uniform in azimuth about the vertical $V V'$, is 0.593 in terms of the intensity $O G$ as unity. The new construction is as follows:

First select the number of zones to be employed in altitude. In Fig. 17 there are three such zones, of 45° each. The upper hemisphere has one 45° zone, $H O B$. The lower hemisphere has two 45° zones, *i.e.*, $H O G$ and $G O V'$. Mark off the middle angular points of the zones, *viz.*, $O E$, $O F$, and $O K$, which will be at elevations of $+22\frac{1}{2}°$, $-22\frac{1}{2}°$ and $-67\frac{1}{2}°$ respectively.

Commence, say, in the upper hemisphere. With center O and the radius $O E$ of the midzone, draw the arc $A E B$ through an angle of 45°. Draw the line $O B$ to the end of this arc.

Turning next to the lower hemisphere, describe an arc with center O and the radius $O F$ of the first midzone, to M, through 45°. Connect O and M by the line $O M$. Measure back along $M O$ a distance equal to the radius $O K$ of the second midzone, and mark off this distance at a point which shall serve as the center of the next arc. It happens in this particular case that the new point coincides with the point O. With that point as center, and with radius $O M$, draw another 45° arc from M to V'; so that $O V'$ makes an angle of 45° with $O G$, and also 90° with $O H$. Draw the line $O V'$.

Take any convenient point, such as H, on the horizontal line, and draw a perpendicular $Q Q'$ through the same, parallel to $V V'$. In some cases it may be convenient to employ $V V'$ itself, without erecting the new vertical $Q Q'$. Project the terminal points B and V' horizontally upon $Q Q'$. Bisect the intercept $Q Q'$ in R. Then either the distance $Q R$ or $Q' R$ will be the mean spherical intensity of the luminous source, to a degree of approximation depending upon the accuracy of the graphical construction and upon the number of zones selected. In Fig. 17 the distance $Q' R$ is 0.598 if $O G$ is unity. It is easy to show that if the geometrical construction were made without error, and $Q' R$ were scaled correctly, the length would be 0.5973 as far as four significant figures. Comparing the actually measured length 0.598 with the theoretically deduced value of 0.5933, it will be seen that in this instance, with only three zones, the result of the graphic construction is correct within 1 per cent. As a general rule, however, 45° zones may introduce an error of two or three per cent. The apparent spherical reduction factor $= Q' R/O h$.

Moreover, since the total flux of light emitted by a virtual point source is 4π times its mean spherical intensity, it follows that if a circle were drawn with radius $Q Q'$, the length of the circumference would be equal to the total luminous flux emitted by the source O. Further, if the polar intensities are scaled in candle-power, then $2\pi\ Q Q'$, or $7.52 \times O G$ will be the total luminous flux in lumen-candles. If the polar intensities are scaled in hefners, then $2\pi\ Q Q'$ will be the total luminous flux in lumen-hefners. Further, the total flux in the upper hemisphere will be $2\pi\ Q H$ lumens, and the total flux in the lower hemisphere will be $2\pi\ H Q'$ lumens. If we should desire to know how much flux is emitted between the horizontal plane and the depression-angle 45°, we should measure H —45, and multiply by 2π. Similarly 2π times the distance along $Q Q'$ between any two projected points is equal to the total flux emitted in the angular zone between the corresponding points in the polar curve. Or, expressing the same condition in another way, the distance along $Q Q'$ between any two projected points is numerically equal to the flux in lumens per radian of azimuth, emitted in the corresponding zone on the polar diagram.

Again, $H Q$ is the mean upper hemispherical intensity, $H Q'$ is the mean lower hemispherical intensity, and the mean spherical intensity is seen to be the arithmetical mean of these two hemispherical intensities.

In Fig. 18 the same construction is repeated, using zones of 30°, instead of zones of 45°. We thus introduce more steps into the geometrical work; but we tend to attain a higher degree of precision in the final result.

As before, mark off the zones of 30°, *viz.*, *A O B* in the upper hemisphere, and *H O J*, *J O T* and *T O V′* in the lower hemisphere. Then mark off the middle angular points in these zones at +15°, –15°, –45° and –75° respectively. These points on the polar curve will form the successive radii of the arcs to be drawn.

Commencing, say, with the lower hemisphere, with center *O* and radius *O* –15°, draw the 30° arc, *H* –15°, *J*. Join *O J*. With distance *O* –45°, the second midzone radius, measure back, along *J O* produced, a distance *J L*.

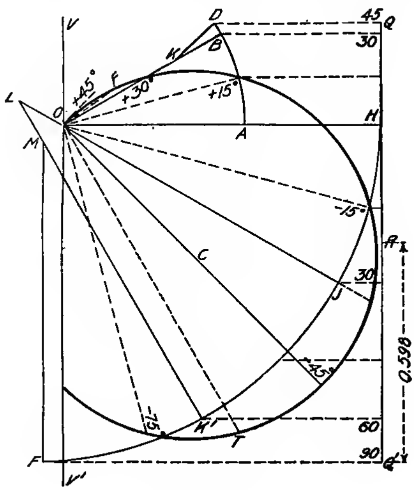


FIG. 18.

With center *L* and radius *O* –45°, continue the arc downwards from *J* through 30° to *K′*; so that *J L K′* = 30°, and *L K′* makes an angle of 60° with a horizontal through *L*. Join *L K′*. With distance *O* –75°, the third midzone radius, measure back along *K′ L* a distance *K′ M*. With center *M* and radius *O* –75° continue the arc downwards from *K′* through 30° to *F*. Join *M F* which will be parallel to *V V′*.

Turning to the upper hemisphere, with center *O* and radius 0+15° of the first midzone, describe the arc *A*,

+15°, *B*. Join *O B*, which will make an angle of 30° with *O A H*. There now remains only part of a zone to be covered in the polar curve; namely the zone +30°, *O*, +45°. Take the middle angular point *O F*, at the elevation +37.5°. With distance *O F*, measure back along *B O* the point *K*. With center *K* and radius *O F*, continue the arc from *B* upwards for 15° to *D*. Join *K D*, which will be inclined at an angle of 45° with *O H*.

Project horizontally the terminal points *D* and *F* upon any convenient vertical line *Q Q′*. Bisect *Q Q′* in *R*.

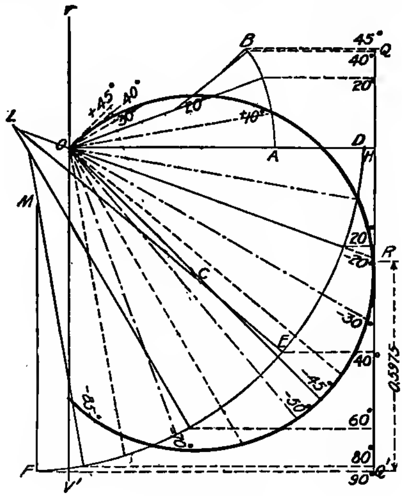


FIG. 19.

Then *Q′ R* will be the mean spherical intensity. In Fig. 18 this distance measures 0.598, if *O G* is unity, or the same as in Fig. 17. Since the horizontal intensity *O H* is 0.7071, the apparent spherical reduction factor by either of the constructions in Figs. 17 and 18 is $\frac{0.598}{0.7071}$ = 0.846, or 84.6 per cent.

The same process of construction is followed in Fig. 19, on the same polar curve; except that the zones are of 20° instead of 45°, or of 30°. Unless the more numerous steps in the geometrical work offset the greater degree of precision in selecting the midzone radii, we should expect a greater degree of accuracy in the result. The curve of arcs in the upper hemisphere, consists of two 20° arcs with radii of O and K respectively, followed by a little 5° arc at B, with the radius at $0+42.5°$ the middle of the zone left over. In the lower hemisphere the curve of arcs proceeds by 20° shifts along $D\ E\ F$ until the last one which is the $-80°$, $-90°$ arc and which is drawn for 10° only, with the radius O $-85°$ on the polar curve. Finally half the distance $Q\ Q'$ measures 0.5975 on the diagram, which is

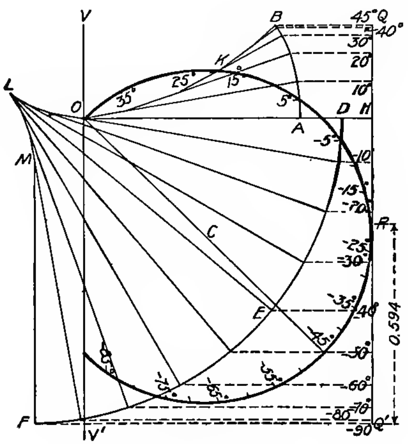


Fig. 20.

within 0.76 per cent. of 0.5933, the theoretically correct value.

Finally, the same process of construction is presented in Fig. 20 applied to the same polar curve, but working with 10° zones. The half of the projected distance $Q'\ R$ measures 0.594, which agrees with the theoretically correct value within 0.17 per cent. or about one part in 600.

In practice, 20° zones are recommended for reliable work, and in many cases 30° zones are sufficiently small; because the degree of precision of the polar curve rarely warrants a higher degree of geometrical work than 30°

zones will produce. It is unlikely that zones smaller than 10° will be found advantageous.

Referring particularly to Fig. 20, it will be seen that the geometrical process resolves itself into producing from the given polar curve two other curves and a straight line of projection. The first curve of arcs, *D E F* or *A B*, may be called the involute curve. The second curve of centers, *O L M* or *O K B*, may be called the evolute curve. Successive tangents on the evolute curve form successive normals to the involute curve. Moreover, if a string without slack were fastened at *L* of length equal to the maximum intensity *O*—45°, and were furnished with a pencil at the free end; then after sticking pins in the paper at the successive centers, *M O*, etc., the string, when moved from one side to the other, would describe with the pencil the involute arc *D E F*. The same condition applies to the upper hemisphere.

Theory of the method.

The mean spherical intensity of a luminous source having equal intensities in azimuth and occupying a virtual point is

$$I_m = 0.5 \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} I_\theta \cos\theta \, d\theta \text{ candle-power or hefners} \quad (1)$$

where I_θ is the luminous intensity at the elevation θ. Let there be n equal zones each of $\frac{\pi}{n}$ radians. Then the above equation becomes:

$$2I_m = \int_{-\frac{\pi}{2}}^{-\frac{\pi}{2}+\frac{\pi}{n}} I_\theta \cos\theta \, d\theta + \int_{-\frac{\pi}{2}+\frac{\pi}{n}}^{-\frac{\pi}{2}+\frac{2\pi}{n}} I_\theta \cos\theta \, d\theta + \ldots\ldots$$

$$+ \int_{\frac{\pi}{2}-\frac{2\pi}{n}}^{\frac{\pi}{2}-\frac{\pi}{n}} I_\theta \cos\theta \, d\theta + \int_{\frac{\pi}{2}-\frac{\pi}{n}}^{\frac{\pi}{2}} I_\theta \cos\theta \, d\theta, \text{ in hefners.} \quad (2)$$

In each of the above n terms, I_θ can differ but little from its value at the midzone. We can, therefore write without much error.

$$2I_m \simeq I_{-\frac{\pi}{2}+\frac{\pi}{2n}} \int_{-\frac{\pi}{2}}^{-\frac{\pi}{2}+\frac{\pi}{n}} \cos\theta \, d\theta + 1_{-\frac{\pi}{2}+\frac{3\pi}{2n}} \int_{-\frac{\pi}{2}+\frac{\pi}{n}}^{-\frac{\pi}{2}+\frac{2\pi}{n}} \cos\theta \, d\theta + \ldots .$$

$$+ I_{\frac{\pi}{2}-\frac{3\pi}{2n}} \int_{\frac{\pi}{2}-\frac{2\pi}{n}}^{\frac{\pi}{2}-\frac{\pi}{n}} \cos\theta \, d\theta + I_{\frac{\pi}{2}-\frac{\pi}{2n}} \int_{\frac{\pi}{2}-\frac{\pi}{n}}^{\frac{\pi}{2}} \cos\theta \, d\theta, \text{ in hefners.} \quad (3)$$

It will be seen by inspection that the construction in Figs. 17–20 makes $QQ' = 2I_m$ and that the projection of each arc in the involute curve on the line QQ' corresponds to one term on the right hand side of (3).

The construction of the involute curve may be seen to express the relation

$$s = \int_0^{\frac{\pi}{2}} I_\theta \, d\theta, \text{ in units of length}$$

and

$$\int_{-\frac{\pi}{2}}^{0} I_\theta \, d\theta, \text{ in units of length}$$

in the upper and lower hemispheres respectively.

When the zones are taken of 20°, it is advantageous to select as their midangular elevations +80°, +60°, +40°, +20°, +0°, –20°, –40°, –60°, –80°. This leaves no uncompleted arc at either terminus, and it avoids any discontinuity in the involute curve at the horizontal line. The first arc is drawn from +10° to –10° with the radius equal to the mean horizontal intensity.

The use of the Rosseau and Kennelly diagrams are satisfactory for comparing incandescent lamps and sources whose candle-power is unvarying, but for determining the mean spherical candle-power of arc lamps and similar sources where the light fluctuates badly it is desirable to employ means whereby the result can be obtained by one photometrical setting. This is accomplished very satisfactorily by means of an integrating photometer of either the mirror or the spherical type.

The **mirror photometer** was first designed by Professor Mathews for use in the laboratories of Purdue. By means of it the mean spherical candle-power of any source can be determined by one reading, but it is especially intended for arc light photometry. A more complete description of the apparatus and a mathematical treatise of the subject is given in the A.I.E.E. Transactions of 1901, and in the Bulletins of the Bureau of Standards of 1905.

The theory of the method as given by Professor Mathews is as follows:—A spherical surface concentric with the lamp is considered and its area divided into zones. Then if I_a be the intensity at an angle a to the vertical, the product of the intensity I_a and the area of an elementary zone of radius r is

$$I_a \, d\, S = I_a \times 2\pi \, r \, R \, d \, a$$

$$= 2\pi \, R^2 \, I_a \sin a \, da.$$

The mean spherical intensity is

$$I_{ms} = \int \frac{I_a \, d\, S}{4\pi \, R^2}$$

$$= \tfrac{1}{2} \int_0^{\pi} I_a \sin a \, da.$$

The mean hemispherical intensity is

$$I_{mhs} = \int_0^{\frac{1}{2}\pi} I_a \sin a \, da.$$

If the intensity I_a be taken at n equal intervals through 180 degrees or n' equal intervals through 90 degrees in a vertical plane, then we may write for the mean spherical intensity

$$I_{ms} = \frac{\pi}{2n} \sum_0^{\pi} I_a \sin a.$$

and for the mean hemispherical intensity.

$$I_{mhs} = \frac{\pi}{2n'} \sum_0^{\frac{1}{2}\pi} I_a \sin a.$$

These expressions are quite correct if n and n' are sufficiently large.

In order to produce on the photometer screen an illumination proportional to the mean spherical intensity of the source, it is necessary to direct toward the photometer beams of light from various angles in the vertical plane. It is furthermore essential that these rays, representing the intensity of light at the respective angles, be reduced in intensity in the ratio of the sine of the angle which the rays make with the vertical, in order that the light from each mirror shall be proportional to the area of the zone which it represents. In developing this method a ring of 24 large trapezoidal mirrors, placed one every 15 degrees, surrounds the arc. The inclination of the mirrors to the arc is such that 24 images of the lamp are presented to the eye placed at the photometric device. Direct rays from the lamp are intercepted by a black screen. The reduction of the light in the ratio of the sine of the vertical angle is accomplished by means of a polygonal glass disk composed of as many sectors as there are mirrors and which are smoked sufficiently to give the desired absorption.

One essential condition to the success of this piece of apparatus is, that the screen shall receive through each sector only the light from its corresponding mirror. The sector disk can be adjusted by replacing the screen by a cardboard pierced by a small opening and by sighting through this hole the disk can be placed with reference to the mirrors. Mirrors of good quality French plate glass were used and their reflection coefficients were carefully determined for the angle of incidence at which they were used, the maximum difference from the mean value of 0.815 was only ± 2.9 per cent. which was corrected by smoking the corresponding sectors. The smoking of the disks was accomplished by burning small quantities of turpentine in a receptacle in which the sector, with a

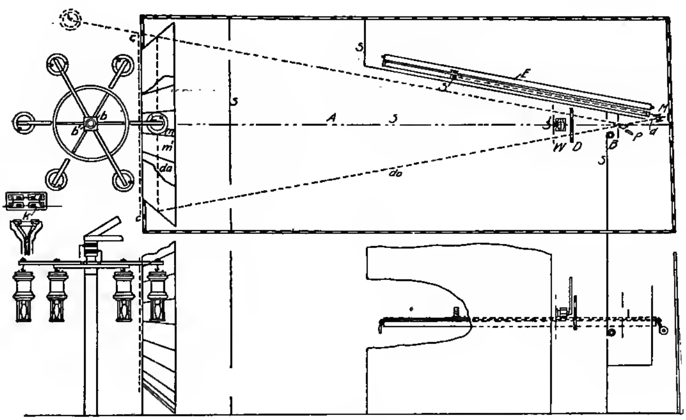


Fig. 21.

guardring to insure even density, is placed in a vertical position.

In the photometer described by Professor Mathews, a plan of which is shown in Fig. 21, the light from the standard lamp, because of the small size of the room, was reflected onto the screen by means of another mirror, *M*. The illumination on the side of the screen toward the arc lamp, being very intense, was reduced by means of a rotating disk provided with a large number of slots.

The complexity involved in determining the working equations for a potometer of this type can be best understood from the deduction given by Professor Mathews for the apparatus illustrated in Fig. 21. He lets

d_a = distance from arc lamp to the photometer screen.
d_s = distance from standard to photometer screen.
K_0 = reflection constant of the horizontal mirror.
K_g = transmission constant of clean glass.
K_s = reflection constant of mirror of the standard.
K_w = transmission constant of the sector wheel.
n, n' = number of mirrors.
f = factor due to the lack of normal incidence.

The illumination due to the arc is

$$i = \frac{2\,K_0\,K_g\,K_w\,f \sum_0^{\pi} I_a \sin a}{d_a^2}$$

and that due to the standard lamp of intensity I_s is

$$i_s = \frac{f\,K_s\,I_s}{d_s^2}.$$

Equating these two expressions, we have for the mean spherical intensity

$$I_{ms} = \frac{\pi}{2n} \sum_0^{\pi} I_a \sin a$$

$$= \frac{\pi\,K_s}{4\,n\,K_0\,K_g\,K_w} \cdot \left(\frac{d_a}{d_s}\right)^2 I_s.$$

Similarly for the mean hemispherical intensity

$$I_{mhs} = \frac{\pi}{2n'} \sum_0^{\frac{\pi}{2}} I_a \sin a$$

$$= \frac{\pi\,K_s}{4n' \cdot K_0\,K_g\,K_w} \cdot \left(\frac{d_a}{d_s}\right)^2 I_s.$$

With the following numerical values

$$d_a = 865 \text{ cm.}, \quad n = 12, \quad n' = 7,$$

$$K_0 = 0.812, \quad K_g = 0.690, \quad K_s = 0.901, \quad K_w = 0.090$$

These equations reduce to

$$I_{ms} = 1.17 \left(\frac{865}{d_s}\right)^2 I_s$$

and

$$I_{mhs} = 2.01 \left(\frac{865}{d_s}\right)^2 I_s,$$

which are the working equations for this apparatus.

If the arc is fed by hand, a smaller number of readings is necessary in order to obtain a fair average value of the candle-power, than when the arc regulates normally. To obtain a distribution curve it suffices to uncover the mirrors in pairs and make sittings in the usual way. The smoked glass sectors must of course be removed and the proper mirror constants used in working up the results. Tests checked by other methods indicate that this apparatus is very reliable considering the fluctuating values of the light from the automatically fed arc.

The **Leonard photometer** is of more recent design than the Mathews photometer although similar in theory and construction. The chief difference between the two being, that the Leonard photometer has its mirrors located at intervals corresponding to the middle points of successive zones of equal areas. Thus the average of the light thrown upon the screen represents directly the mean spherical, or the mean hemispherical candle-power, as the case may be, without the intervention of smoked sectors.

Prof. Ulbrich's **spherical-photometer**, which also permits the measurement of the mean spherical candle-power of a lamp by a single setting, consists in part of a large sphere, with its inner surface painted white. The source of light to be measured is placed inside of this sphere and the illumination at an opening in the surface of this sphere (the direct rays being intercepted by a screen) is proportional to the mean spherical candle-power of the lamp. A globe of this kind integrates very successfully the illuminating effect of any source. It involves in addition a photometric device and a standard incandescent lamp.

The general theory of the spherical photometer, according to Dr. Bloch, is as follows: When a source of light is placed inside a spherical shell having a matt surface, the light received by any part of the interior surface can be considered in two parts—(a) that coming directly from the lamp, and (b) the light received from the remainder of the interior surface of the sphere after one or more reflections. The quantity (a) is that which is measured in the ordinary photometer which determines the intensity

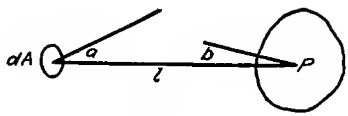


FIG. 22.

of light emitted in any one direction, and is not considered at all in the globe photometer. According to the theory of the globe photometer the quantity (b) is constant all over the surface of the shell, and is proportional to the total amount of light emitted by the lamp, quite independent of its position in the shell.

The theoretical argument for this photometer is as follows: Assume a surface P (Fig. 22) to be illuminated by radiation from a small luminous area $d\,A$, the brightness of which is B; then the light received on a unit area at P is

$$\frac{B\,d\,A \cos a \cos b}{1^2}$$

a and b being the angles which l makes with the normals to the two surfaces. If now we let Fig. 23 represent a section through the photometer into which is inserted for measurement a lamp L, indicated in the figure, and consider the illumination of the surface at the point P by light reflected from a small area $d\,A$, and the circle shown be a section through the point P and the area $d\,A$, then the light received on $d\,A$ from the lamp directly will be $I_A\,.d\,A$, and the $\int I_A\,.d\,A = E$, the total light emitted by the lamp. The intensity of $d\,A$ is $k\,I_A$, since the surface is perfectly matt and throws the light in all directions equally, k being the reflection constant for the surface. The light received from this surface $d\,A$ at P once reflected is

$$\frac{k\ I_A\ d\ A\ \cos^2\ a}{l^2} = \frac{k\,I_A\,d\,A}{4\,r^2}.$$

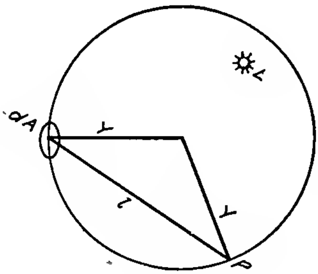


FIG. 23.

Hence the illumination at P due to once reflected light from the whole surface of the sphere will be

$$\frac{k}{4\,r^2}\int I_A\ d\ A = \frac{k}{4\,r^2}\ E.$$

It follows at once that the illumination at P by light twice reflected will be

$$\left(\frac{k}{4\,r^2}\right)^2 E.$$

The total illumination at P due to reflected light is

$$E\,(k/4\,r^2 + (k/4\,r^2)^2 + (k/4\,r^2)^3 + \ .\ .\ .\ ) = K\,E,$$

where K is the constant of the instrument and depends on the size of the sphere and the quality of the interior surface.

Thus we can see that the illumination of the interior of the sphere is theoretically uniform and proportional to the total light emitted by the lamp; therefore, if we screen off a small area from the direct rays of the lamp, the remaining illumination of that area is proportional to the mean spherical candle-power of the lamp.

If the lamp be removed to the surface of the sphere so that the center of the source is directly in the surface, then a single measurement will give a value proportional to the mean hemispherical candle-power. The ratio of

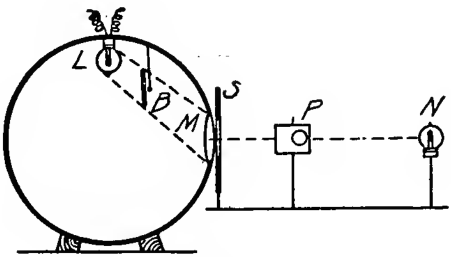


FIG. 24.

proportionality being one half that in the determination of the mean spherical candle-power.

There are two sources of error in this method, one is likely to occur by the lamp not being in the center of the surface, while the other is due to the non-transparent fittings of the lamp which intercept part of the light. Experiments show that errors due to the latter cause greatly outweigh those due to the former, but that a compromise can be made sufficient for all practical purposes if the lamp is not supported at the center but at a distance of 8 or 15 per cent of the diameter from the top of the inner surface of the sphere; also by making the globe very large.

The construction of this photometer is shown in Fig. 24 where L and N are the two lamps, P the photometric device, S a screen whose aperture can be varied and M is the window of some translucent material protected from the direct rays of the lamp by the screen B.

Experiments with globe photometers give results very consistent with those obtained from "point-to-point" readings, and tests of a great many different sources of light show that the mean spherical candle-power can be obtained by this arrangement with an error of not more than three per cent. The apparatus can be calibrated by means of a lamp of known mean spherical candle-power placed at the center of the sphere. The most satisfactory surface for the inner side of the sphere appears to be a coating of lithopone (barium sulphate). This instrument highly recommends itself for the photometry of arc lamps.

CHAPTER V.

STANDARDS OF ILLUMINATING POWER.

The standard unit of illuminating power was, for a long time, the light of a candle made to certain specifications and consumed at a given rate; and it has been the almost universal custom to refer the intensity of light sources to that of the candle and to designate their illuminating property in terms of the candle-power. The action of the American Institute of Electrical Engineers and the National Electric Light Association in giving official indorsement and legalizing the amyl acetate or Hefner lamp as the standard of illuminating power, has rendered all forms of candles obsolete for light standards.

A practical standard of illumination should be simple in construction and operation, durable in all its parts, constant in operation, and capable of being reproduced with accuracy. All flame standards are subject to errors other than those due to the constitutents involved. In 1859 Frankland and Tyndall made some interesting experiments concerning the effect of atmospheric pressure on the illuminosity of a flame and the amount of combustible consumed. They found that combustion was unaffected by atmospheric pressure but at low atmospheric pressures, such as occur at the top of Mt. Blanc, the candle became as non-luminous as the Bunsen burner, while by increasing the pressure an alcoholic flame becomes white and luminous. The conclusion being that the variation in the illuminating power of a flame depends chiefly on the access of atmospheric oxygen as regards the interior of the flame.

When a chemically inert gas or vapor is introduced into a luminous flame there usually results a decrease of its illuminating power. In this way non-combustible constituents of the atmosphere, such as aqueous vapor and carbon dioxide, may be expected to influence the light value of all flames, and as the proportions of these substances are all the time changing and especially so in the average photometer room, they must introduce errors in flame measurements. Methven found that a standard candle, burning at a constant rate of 120 grains per hour, gave an illumination of 1.196 units when burning in dry air while the illumination was only 1.104 units, or a decrease of 8 per cent, when burning in moist air under the same conditions of flame height and consumption.

The flame standards of illumination which have been used to quite an extent in the past and some of which are still being used extensively, especially in the gas industry, are the English and German candles, the Carcel lamp, the Methven screen, the Pentane standard, and the Hefner lamp.

The **English candle** is made of spermaceti, carefully prepared from the oil of the sperm whale. It has been subjected to various investigations and extended series of measurements performed with great accuracy and care have led to its almost universal condemnation as a standard of illumination. Its faults appear to be the uncertainty in the composition of the spermaceti and in the weaving of the wick, the variation in the length and shape of the wick while burning, the filling and emptying of the cup of the candle, and the adventitious circumstances attending its use, which, as a whole, it is not possible to regulate or define.

The **German candle** is constructed under unusually minute specifications as to both wick and combustible. The combustible is paraffin highly purified and having a melting point of 55 degrees centigrade. But paraffin being a mixture of indeterminate composition is unsuited for a standard of illuminating power, moreover the general features detrimental to the English candle apply to this candle as well.

In addition to the English and German candles there are a number of less widely used standard candles but they possess no essential differences from the two described. The unreliability of the candle lead to the development of more constant and trustworthy standards.

The **Carcel lamp** having a central draft type of burner, known as the Argand, and burning oil furnishes a flame of remarkable steadiness and of marked whiteness of light. It was developed in 1802 by Carcel and attained great favor in France. It was fully investigated as a light standard, and its constants and dimensions carefully determined and defined. Until recently it was the recognized standard of that nation, where the illuminating power of light sources has been invariably expressed in terms of the Carcel unit. The combustible generally employed was Colza oil. This lamp was not received with favor by the other countries, the objections being similar to those of the candle.

The **Methven screen** as a standard consists of an argand burner gas lamp provided with a screen in which is an opening so placed as to be opposite the center of the flame. On this screen is mounted a thin slide with two rectangular openings, one for plain gas and the other for carburetted gas. The theory of this type of standard was, that the light received from the central part of a flame only would be more constant than if received from the whole flame. The height of the flame is gaged by two pins one on either side of the chimney.

Upon careful investigation of the Methven screen it was found not to be sufficiently constant and reproducible to serve as a standard of illumination.

Harcourt's **pentane standard** is used extensively as the standard of illumination in the gas industry of England. It was recommended by a committee on photometric standards appointed by the Board of Trade of London in 1881 as being the most reliable standard of the time and it was accepted by that Board as the standard of illumination. This lamp burns air-gas made by bringing together air and pentane in the proportion of one cubic foot of air to three cubic centimeters of pentane. The burner is of special design, having a 0.25-inch opening in the top to allow the gas to pass. This burner is surrounded by a glass cylinder and openings around its base admit air. The gas may be conveniently prepared in a gas holder, consisting of a cylindrical bell suspended and counterpoised in the usual manner, over a tank having an annular space filled with water.

Variation of temperature, atmospheric pressure, and humidity affect the absolute value of the light which this standard yields, and should be corrected for where absolute measures are concerned, but they do not affect comparisons made between this standard and other hydrocarbon flames.

Of the light standards, the **amylacetate lamp,** or simply the **Hefner lamp** is by far the most worthy of its position. It has been subjected to thorough and accurate investigations and its faults as well as its merits are clearly understood.

The Reichsanstalt lamp has been universally adopted as the standard for the use of amyl acetate. The material of construction is of brass except the wick-tube which is of German silver to prevent corrosion by the combustible. Liebenthal found that an increase or decrease of one millimeter in the diameter of the wick tube caused a decrease of one per cent in candle-power. The wick is moved by means of a worm gear which actuates two spur wheels shown in Fig. 25. All of the fittings of the lamp are attached to the wick tube which unscrews from the cup for filling. The character of the wick has practically no influence on the candle-power of the lamp, since amyl acetate vaporizes at such a low temperature that the wick does not project into the flame and burn. A metal cap is kept screwed down over this wick when the lamp is not in use.

A test gage is furnished with each lamp for the purpose of adjusting the height of the flame which burns with greatest constancy and steadiness when about 40 millimeters in height. Accuracy in setting the flame is essential since a variation of one millimeter in height will produce three per cent difference in the illuminating power. The illuminating power of the Hefner lamp, according to

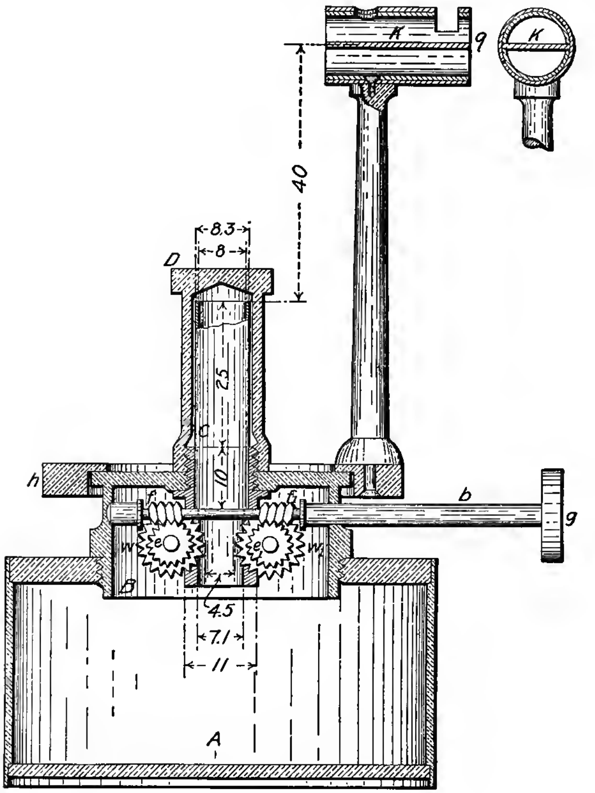


Fig. 25.

Liebenthal, can be expressed as a linear function of the flame height, the equations for wnich are:

$$i = 1 + 0.025\,(h - 40)$$

and

$$i = 1 - 0.034\,(40 - h)$$

for heights of flames greater than 40 millimeters and less than 40 millimeters respectively.

Herr von Hefner-Alteneck, the inventor of this lamp, pointed out and insisted on the necessity of using a combustible of known chemical composition. Amyl acetate, because of its chemical simplicity and definite composition, is excellently fitted for the combustible of a standard. It is a colorless liquid and has the chemical constitution of $C_7 H_{14} O_2$ and burns with a clear flame, of not great brilliancy and of a somewhat reddish color; it is obtained from the distillation of amyl alcohol obtained from fusil oil, with a mixture of acetic and sulphuric acids: or by distilling a mixture of ethyl alcohol, sulphuric acid, and potassium acetate. The presence of impurities, which are most common in amyl acetate, has but very little effect upon the value of the light from this lamp. The results of tests to ascertain the influence of these impurities are given in the following table:

Amyl acetate diluted with	Specific gravity	Hourly consumption in grains	Deviation from normal consumption in per cent	Deviation from normal intensity in per cent
20 per cent fusil oil.........	0.8645	9.96	+6.9	—2.0
2 per cent diamylen.........	0.8725	9.24	—0.8	0.0
5 per cent alcohol and 4 per cent castor oil...........	0.8745	9.88	+6.0	Impossible to determine
10 per cent isobutyl acetate and 10 per cent amyl alcohol	0.869	9.28	—0.4	+0.4
50 per cent alcohol..........	0.8403	12.92	+39.0	+40.0
Pure amyl acetate	0.8735	9.318	——	——

Amyl acetate for photometric purposes should be chemically pure, the tests to determine this condition as prescribed by the Reichsanstalt are as follows:

1. The specific gravity at 15 degrees centigrade should be from 0.872 to 0.876.
2. Ninety per cent should distill between the temperature limits of 137 and 143 degrees centigrade.
3. The reaction should be practically neutral.
4. It should mix with equal volumes of ether, benzine, or carbon-bisulphide, without becoming milky.

5. A clear solution should result upon shaking in a test tube, 1 cu. cm. amyl acetate with 10 cu. cm. ethyl alcohol, 90 per cent Trallar, and 10 cu. cm. of water.

6. A drop placed on white filter paper should evaporate without leaving a grease spot.

Amyl acetate should be kept in a glass-stoppered bottle and, as it has a tendency to decompose in strong light, it should be stored in a dark place, or in opaque vessels.

The effects of temperature due to the lamps itelf are rendered negligible by the thinness of the walls of the tube, while atmospheric temperatures have no discernable influences.

Atmospheric moisture, however, is not without its effect. Data showing the monthly averages for the light of the Hefner lamp for one year, vary from 101.9 per cent normal candle-power for February to 97 per cent for July. During March, April, May, October, and November the average intensity was normal. For June, July, August, and September the average was about 2 per cent below normal and for December, January, and February the average was about 2 per cent high. The results of tests extending through a period of two years showed a maximum difference of 8.5 per cent, or 103.3 per cent in January and February, and 94.8 per cent in May and July. Hence this lamp can be relied upon to give values within 4 per cent of the normal standard candle-power. The equation correcting these results for humidity is

$$y = 1.049 - 0.0055\,x,$$

where y is the illuminating power of the lamp with x liters of moisture to the cubic meter of air, free from carbon dioxide and at normal pressure. The intensity decreases uniformly by an amount equal to 0.55 per cent per liter.

Carbon dioxide has an effect similar to humidity. The expression, correcting for its effect on the candle-power between the limits of 0.6 and 13.7 liters per cubic meter is

$$y' = 1.012 - 0.0072\,x;$$

y' being the candle-power, and x' the number of liters of carbon dioxide to the cubic meter of dry air, hence a variation of one liter of carbon dioxide to the cubic meter of air causes a change of 0.7 per cent in the candle-power.

By comparing the equations for moisture and carbon dioxide corrections it will be seen that the effect is not the same but as 1 to 1.3 for the same amount of each in the air. Yet in reality, the effect of carbon dioxide is slight compared with the influence of moisture because of the smaller quantity present. These equations show that the lamp has unit candle-power when there are 9 liters of moisture and 1.7 liters of carbon dioxide to the cubic meter of air. In well ventilated photometer rooms the amount of carbon dioxide present will not cause a change in intensity of more than 0.2 per cent, but in small rooms and especially in all enclosed photometric apparatus there may arise considerable error, since the air in them is not only soon vitiated to a marked degree by the addition of water vapor and carbon dioxide but by the removal of the oxygen.

The correction for atmospheric pressure, resulting from thorough investigation, is

$$\Delta y = 0.00011\,(b - 760),$$

Δy being the change in illuminating power based on unit value y for the normal atmospheric pressure of 760 millimeters. b is the reading of the barometer expressed in millimeters. This equation represents a variation of 0.1 per cent per centimeter change in the barometer reading.

Tests as to the accuracy and constancy of the Hefner lamp have given very satisfactory results.

The chief objection to this lamp as a standard is that the flame is too red in color and is liable to introduce errors in photometry due to the Purkinje effect.

From the preceding pages the effect of atmospheric irregularities on flame standards can be easily understood. Such complexities go to emphasize the desirability of a standard for photometric work free from such disturbances.

The **arc standard** has been proposed as a standard of illumination. The intrinsic brightness of the positive crater for a given carbon, according to Violle, is constant and independent of the watts absorbed by the arc over a wide range. Moreover the brightness and wave lengths of the different color groups remain unchanged. It was suggested that the light emitted from a portion of such a crater would make a reliable standard but the quality of different carbons, both physical and chemical, is so non-uniform and affects the amount and color of the light to such an extent that the arc standard has not yet materialized into a practical form, although it seems to merit further consideration and investigation.

The **Violle standard,** which appears to be constant under varying conditions, consists of the illumination from one square centimeter of incandescent platinum. The exceedingly high temperature at which platinum liquifies makes this standard unsuitable for laboratory work. The results of investigation show, however, that molten platinum merits significance as a possible absolute standard, since it does not oxidize and can be obtained in a sufficiently pure state. The Bougie candle (page 10) is equal to 0.05 of the Violle standard.

The **incandescent lamp,** aside from its illuminating value, is of inestimable value as a secondary or comparison standard of light. The incandescent lamp has probably been of more service in photometry than any other source of light, because of the constancy of the illuminating power of a particular filament under proper conditions. This has made possible concordant data and a quantitative knowledge of the variations in flame standards. The color of the light from an incandescent lamp can be varied by changing the voltage so as to resemble the compared light, they may be moved along the photometer bar and are more convenient as to portability, when a low voltage lamp may be used in junction with a storage cell.

The illuminating power of a lamp to be used as a secondary standard should be determined from the standards maintained at the Bureau of Standards when possible. If such a course is not feasible it may be calibrated by means of a Hefner lamp and corrections made for atmospheric conditions. It is well to keep one or more carefully standardized lamps for checking the others. It is necessary to know the position of the lamp when standardized and the voltage or current or both in order to be able to reproduce known conditions. Care should be exercised to avoid the influence of temporary set or hysteresis in the resistance of the filament and especially the permanent set due to abnormally high voltages. It should not have voltages impressed upon it much in excess of that at which it was calibrated.

It can be seen from the life curves of incandescent lamps that they are not suitable for a standard until after they have been burned for about 150 hours. After burning this length of time the candle-power is usually constant for several hundred hours, and it is on this part of the curve that the lamp should be standardized. The carbon filament lamp was and is most extensively used for this purpose, the osmium lamp has been used to some extent, and the characteristics of the tungsten lamp indicate properties more desirable for a standard than are possessed by either of those just mentioned.

The Bureau of Standards* made a careful study of the standards of illumination of Great Britain, Germany, France, and the United States for the purpose of establishing a working standard which could be maintained constant and in terms of which lamps submitted could be standardized. They found the British candle to be the recognized standard in the gas industry and the Hefner lamp the standard in the photometry of electric lamps, using the ratio of 1. Hefner equal to 0.88 British candles.

*Bulletins of Bureau of Standards.

The Bureau adopted the British candle as the unit in terms of which the standard of the Bureau should be expressed. They found the candle to be unreliable, giving values varying by 5 per cent. The Hefner lamp was adopted since it was found to vary by not more than 2 per cent from the standards of the Reichsanstalt and is certified by that institution as correct. The Hefner unit was obtained by means of incandescent lamps verified at the laboratories of the Reichsanstalt in terms of their Hefner lamps. The unit of the Bureau was obtained from these lamps by the use of the ratio 1. Hefner equals 0.88 candle-power.

The mean candle-power and mean current of six incandescent lamps tested at the

Bureau of standards...gave	16	candle-power	at	0.5924	amperes
Nat. Physical Lab. Eng...............	" 16.29	"	"	" 0.5925	"
Reichsanstalt, Germany.............	" 16.01	"	"	" 0.5923	"
Lab. Central, France..	" 16.36 bougies			" 0.5917	"

The candle-power, in each case, is in terms of the standard of the respective laboratory and shows the relation between the standards of the four nations. These relations can be more conveniently compared by means of the following table which gives the values of the units of the different laboratories in terms of the unit of the Bureau of Standards:

Bureau of Standards unit, U. S............	1.000
Reichsanstalt unit, Germany.......... ...	0.998 x 0.88
National Physical Laboratory unit, Eng....	0.984
Laboratorire Centrale unit, France..	0.982

Comparative data on the illuminating value of the Harcourt, Carcel, and Hefner lamps, compiled by the Bureau, is given below.

Source of data and method of measurement	Harcourt (10 c-p) / Hefner	Carcel / Hefner	Harcourt (10 c-p) / Carcel
Reichsanstalt, using an electric comparison lamp..............	10.9	10.7	1.02
Laboratorie Centrale, using an electric comparison lamp........	10.76	10.76	1.00
Laboratoire Centrale and Laboratoire d'Essais, direct comparison	10.72	10.73	1.009
National Physical Laboratory.....	10.95	10.69	1.024
Ratios computed from Bureau of Standards incandescent lamps...	11.19	10.73	1.043
Best previous values by Bunte....	11.4	10.87	1.05

The relative values of the various standards described in the preceding pages are given in terms of each other in the following table:

Standard equals	Hefner unit	Bougie decimale	English candle	German candle	Carcel lamp	Harcourt's pentane lamp	Violle's platinum standard
Hefner unit.....	1.	0.917	0.88	0.87	0.092	0.088	0.0458
Bougie decimale	1.09	1.	0.965	0.95	0.101	0.0955	0.050
English candle.	1.13	1.04	1.	0.98	0.104	0.099	0.052
German candle.	1.15	1.055	1.02	1.	0.106	0.101	0.053
Carcel lamp....	10.87	9.97	9.62	9.46	1.	0.954	0.499
Harcourt's pentane 10 c-p. lamp........	11.4	10.45	10.1	9.9	1.05	1.	0.523
Violle's platinum standard	21.8	20.0	19.2	19.0	2.0	1.92	1.

CHAPTER VI.

INCANDESCENT LAMPS.

Light from a primary source is due to the incandescent particles of matter, and it was known for a long time that the illuminating power of a flame could be increased by either increasing the number of these particles of matter or by increasing their temperature or by doing both.

In 1820 Mr. Cameron saturated a piece of wood with bleaching powder and on burning the wood away there remained a white substance which when put in the outer part of a candle flame emitted a brilliant light. Also at about this time Dr. Brewster used the salts of magnesium with similar results; and without doubt, if the rare metals had been more easily procurable, incandescent gas lighting would have dated from that time.

The " lime " light, which was extensively used for scenic illumination on the stage until replaced by the electric arc, consisted of a mass of lime against which was applied the flame from a blast lamp fed with oxygen and illuminating gas. The incandescent gas mantle as invented by Welsbach is the result of research along these lines. The composition of this material is more or less a secret, but consists chiefly of the oxides of some of the rare metals, as thorium and yttrium.

With the advent of electricity the heat effect of the current was utilized for the production of the incandescent source, and although the electric arc was the first successful means of lighting by electricity, we will consider the incandescent lamp first in the following discussion.

The first incandescent lamps of commercial significance in electrical lighting were brought out in 1880. Edison after much experimenting with carbonized thread, paper, etc., finally decided upon bamboo fibre as the most uniform and durable material and his lamps attained great favor. Eventually, the filaments of all lamps except those of high candle-power or of special design were made from soluble cellulose squirted into threads, hardened, carbonized, and treated.

The prevailing method of making the filament is to take some of the fiberous substances as cotton, rid it of impurities, evolve it into a pulp, as in paper making, and dissolve it in some solution as zinc chloride. It is then evaporated to the consistency of thick molasses, and then forced through a die, in the form of fine thread, into an alcohol bath, which hardens it.

Thus made, the filament is of very uniform constitution and size, and after being wound on a form and carbonized, it forms a carbon thread of remarkable strength and flexibility. However, no filament is of uniform cross-section throughout; neither is a durable filament produced from the somewhat porous carbon obtained in this way. After the filament is mounted in the lamp it is immersed in an atmosphere of hydrocarbon vapor and subjected to the flashing process. This has a twofold object; first, it builds up the filament with a dense carbon coating and, secondly, it corrects for any lack of uniformity which may exist.

As the filament is heated by establishing an electric current through it the vapor near it is decomposed and the carbon is deposited upon the filament in the form of a smooth coating almost as dense as graphite and a much better conductor than the original filament. Also, if the filament possesses a part of smaller cross-section than the rest, that part will become hotter than the remaining filament and the deposit there will be greater thus tending automatically toward a uniform filament. The finished filaments are strong and elastic generally of a grayish steel color, and for lamps of ordinary candle-power and voltage, vary from 6 to 12 inches in length and from 5 to 10 thousandths of an inch in diameter. Since platinum has practically the same coefficient of expansion as glass, it is used to make connections with the outer circuit and two small platinum wires, to which the filament is attached by means of carbon paste, are fused in the glass tube at the base of the lamp.

After the connections are made in the lamp and the flashing treatment has been performed, the bulb is attached to an air-pump and the air exhasuted, after which the lamp is sealed. The quality and life of the lamp depend to a great extent upon the completeness and dryness of the vacuum, since any air or moisture remaining in the bulb will oxidize the carbon filament, thereby shortening the life of the lamp and decreasing its candle-power. Moreover, in a lamp with an incomplete vacuum there is more or less loss of energy due to the leakage of electricity through the space around the filament. This electricity so passing gives at most a very pale, bluish light which adds little or nothing to the candle-power of the lamp. No leakage occurs if the vacuum is complete.

All the gases cannot be removed by mechanical pumps, consequently, a gas is introduced into the bulb capable of combining with the residual gases remaining in the bulb rendering them innocuous and securing a vacuum of perfect insulating properties.

The blackening of the bulb, which absorbs more or less light, is caused by a vaporization of the carbon. The amount of the volatilization varies with the character of the filament and the temperature at which the lamp is burned.

It has been found that there is a hysteresis effect in the incandescent filament probably due to some molecular readjustment. The result is that the change in resistance lags behind the change in voltage, the resistance corresponding to a given candle-power being greater if the voltage is increased than if it is decreased to produce the same illumination. To this phenomenon may be attributed the reason for a longer life of a lamp on alternating current than on direct current. This shorter life of the direct current lamp may also be due to a Peltier effect at the junctions of the platinum and carbon or to some electrolytic effect.

There are a great many types of the carbon filament lamp, together with many different methods of manufacturing the filaments and shaping them in the bulbs. In the early lamps a " U " shaped filament was used almost entirely, but the distribution of the light was poor. Later the filament was formed into loops allowing the use of a smaller, more symmetrical bulb and giving a more uniform distribution of light. In order that the distribution of light should be still more even the filament was made in the form of a helix, with its axis lengthwise the bulb as in the Sterling Special, or horizontal, as the lamp is suspended, as in the Shelby or Meridian lamps. One of the recent, as well as the simplest forms of the incandescent lamp is the Linolite. This lamp consists of a glass tube about three-fourths of an inch in diameter and about eight inches long with the filament stretched lengthwise and straight except for a small loop at its center. Electrical connections are made and the tube is sealed at the ends. This lamp is especially adapted to desk and window lighting. Other types of lamps will be described later.

The bulbs of incandescent lamps are often "frosted" in order to lower the intrinsic brilliancy of the source, and give a better distribution of light. This frosting, although successful in diffusing the light, decreases the total amount of light, by absorption, by from 4 to 7.5 per cent. The frosting may be accomplished by means of either acid or sandblast, the effect being the same in either case.

A series of tests,* on lamps of various makes and with filaments of different shapes, were conducted at the Bureau of Standards to ascertain the effect of frosting the bulbs. The distribution curves for the light in a vertical plane and the shape of the filaments, for some of the common types of lamps may be studied from the following diagrams. They are all rated 110 volts, 16 candle-power, lamps; the

*Bulletins of Bureau of Standards.

bulbs are of ordinary shape; *a* and *b* designate the distribution curves for lamps with clear and frosted bulbs respectively. Fig. 26 represents the shape of the filament of and the distribution of light from a typical oval anchored filament lamp. Fig. 27, the double filament lamp, Fig. 28, the spiral filament lamp; Fig. 29, the double round coil filament; Fig. 30, the double flattened coil filament; Fig. 31, the downward-light filament.

Twenty-five lamps of each type were obtained directly

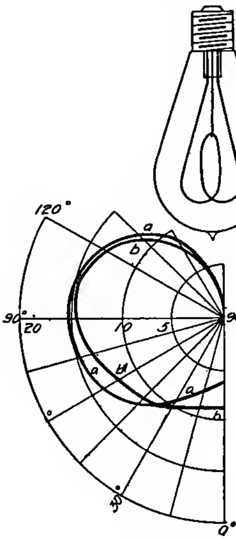


FIG. 26.

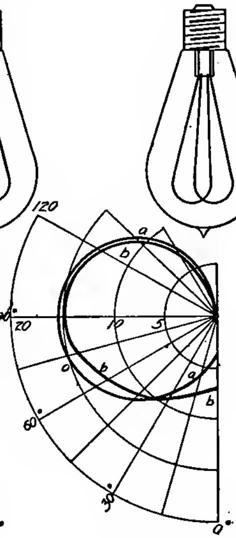


FIG. 27.

from the factories, and all were seasoned before being investigated. Several lamps of each type were carefully calibrated for mean horizontal and mean spherical intensity for use as standards for that type, and all subsequent measurements on lamps of any type were made in terms of the standards of that type.

Data compiled from the Bulletins showing the average values for each of these classes of lamps is given in the table below. The type of lamp will be designated by its figure number.

Lamp (Fig. number).		26		27		28	29	30	31
Lot number.	1 acid	2 acid	2 sand	3 acid	3 sand	4 acid	5 acid	6 acid	7 acid
Reduction factor plain bulb	0.826	0.824	0.828	0.806	0.809	0.914	0.884	0.972	1.064
Reduction factor frosted bulb	0.825	0.825	0.825	0.784	0.797	0.863	0.884	0.984	1.027
Absorption coefficient mean spherical	5.3	3.8	5.6	6.2	7.0	4.7	4.9	6.2	7.5
Absorption coefficient mean horizontal	5.0	4.0	5.4	3.7	5.9	0.9	5.0	7.3	4.2
Initial horizontal candle-power plain bulb	15.31		15.29	15.15	15.26	15.29			
Initial horizontal candle-power frosted bulb		14.55		14.53		15.28		14.48	14.20

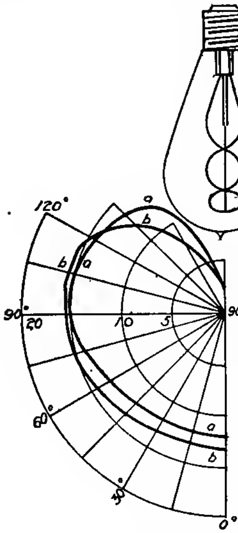


FIG. 28.

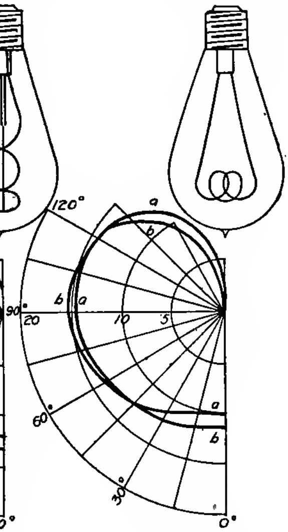


FIG. 29.

Each lot of lamps was measured for mean horizontal and mean spherical candle-power, and then sent to the factory to be frosted. After being returned from the factory the lamps were again measured for mean horizontal and mean spherical intensity. The decrease in mean spherical intensity due to frosting is given as the absorption coefficient in the above table. A study of the lamps with regard to the reduction factors, which is the ratio of the mean spherical to the mean horizontal candle-power, before and after frosting is interesting. It will be seen that this ratio remains practically the same in the anchored filament and the double round coil lamp, while it becomes less with frosting in the double and the spiral filament lamps, and greater in the double flattened coil and the downward light lamps.

The frosting can scarcely be said to absorb light by extinction, it merely diffuses it, and in this diffusion some of the rays which would otherwise pass through the outer

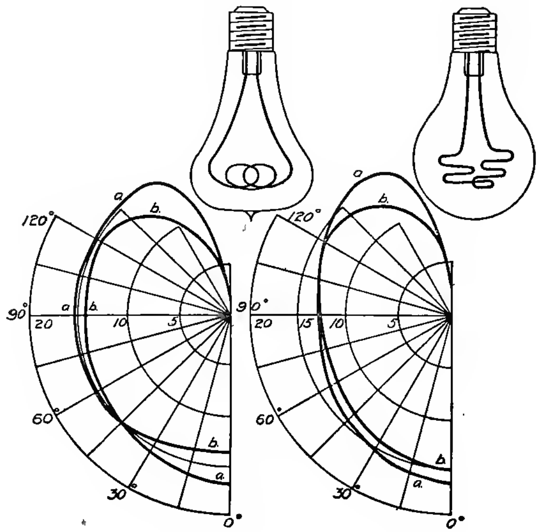


FIG. 30. FIG. 31.

surface of the bulb are compelled to traverse the glass and whatever deposit there may be on the inside of it, a third and fifth time, and since all glass absorbs some light, more will be absorbed by this multi-transmission than would be otherwise. It seems to be the concensus of opinion that the decrease in intensity caused by frosting the bulb and the greater decrease in candle-power of frosted lamps with age is due, not to the frosted surface, but to the glass and the carbon deposit on the inside of the bulb.

The **Meridian lamp** stands apart from the other carbon filament lamps in that it has a large spherical bulb. The filament is of a horizontal helix design. The distribution of light from a 60-watt and a 120-watt lamp are shown in Fig. 32. This lamp is made with a frosted glass globe, with which it closely resembles the Nernst lamp in appearance.

A class of lamps known as "turn down" lamps, and known under the name of the Hylo, Economy, Dim-a-lite and the like have for their object the emission of a small amount of light with a corresponding small consumption

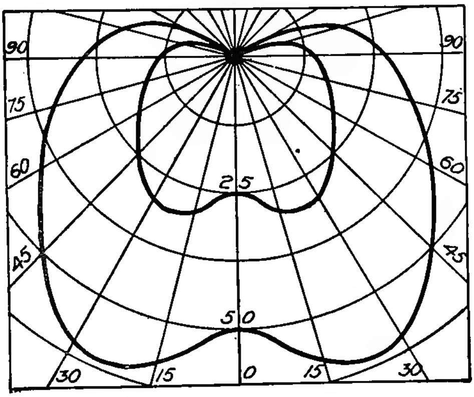


FIG. 32.

of energy. These lamps have either a resistance which can be thrown in series with the filament or a second and smaller filament so connected that the two can be connected in series, the smaller filament giving the light and the other acting as a resistance only.

The specific consumption of a lamp is usually spoken of in terms of the "watts per candle-power" and ranges from 3 to 3.5 watts per mean horizontal candle-power for the ordinary carbon filament lamp. The amount of light obtained from an incandescent lamp depends on the emissivity of the filament and the temperature at which the filament is operated. The emissivity of the filament is greatly affected by the character of its superficial layers; those having a dull black surface have a far greater light-emitting power than those having a surface of a gray color. Moreover, the emissive power of a filament increases with age, the superficial layers taking on an appearance approximating a dull black surface. The temperature and consequently the candle-power of a lamp increases with the voltage. It has been found that the candle-power varies approximately as the sixth power of the voltage and the 5.6 power of the current. Any increase in voltage, however, is accompanied by a decrease in the length of life of the lamp. The following table gives the variation of candle-power and life with voltage.

Per cent. of normal candle-power	Per cent. of normal voltage	Per cent. of normal life
55	90	——
75	95	——
100	100	100
106	101	82–90
112	102	68–80
125	104	45–55
138	106	30–40
——	110	10–20

The candle-power and specific consumption of lamps rated at from 2 to 4.5 watts per candle-power after the same length periods of service are given in the table below. These results represent the mean values of tests on more than 500 lamps of 49 different types and from 28 factories.

Hours service	Initial specific consumption, watts per c-p.									
	2.–2.5		2.5–3.		3.–3.5		3.5–4.		4.–4.5	
	per cent c-p.	watts per c-p.	per cent c-p.	watts per c-p.	per cent c-p.	watts per c-p.	per cent c-p.	watts per c-p.	per cent c-p.	watts per c-p.
0	100	2.4	100	2.9	100	3.3	100	3.8	100	4.5
100	84	2.8	93	3.0	95	3.4	96	4.1	96	4.7
500	48	4.6	71	4.0	79	3.9	77	5.0	75	5.8
1000	37	5.7	56	5.3	64	5.0	60	6.3	60	7.0

The per cent. c-p. values are in per cent. of initial candle-power.

The temperature of the filament under normal conditions should be as high as possible commensurate with an economical life. The temperature, under usual conditions, in the ordinary lamp varies from 1300 to 1500 degrees centigrade.

The choice of lamps for lighting purposes may be determined by the initial cost of the lamp and the price of electrical energy. It is obvious that if the latter is costly, a high-efficiency lamp with a corresponding short life is more economical than a low-efficiency lamp with a long life.

A lamp, in order to give satisfaction, must not only be properly made but it must be properly used. It should be burned at its rated voltage which should remain constant, and it should be replaced when it gets dim. Irregularities in voltage are most noticeable, on power circuits where the load is changeable, and on alternating current circuits where transformers of poor regulation are installed. Under these conditions low-efficiency lamps must necessa ily be used, causing a great decrease in the efficiency of the system and in the output of the station. The specific consumption of the average lamp on power and alternating current circuits is about four watts per candle-power; with good regulation as obtained by modern types of transformers and generators of good design and by the judicious distribution of feeders, 3.1-watt lamps may be used to give the same amount of light, thereby saving 20 per cent. in power consumed and increasing the capacity of the station by the same amount.

The smashing point or the end of the useful life of a carbon filament lamp is when its candle-power has fallen to 80 per cent. of its initial value. Beyond this point it is usually considered cheaper to replace the old lamp with a new one. This relation does not hold for the new class of lamps, which, because of their initial cost and high efficiency, are usually burned until the filament ruptures.

The **Gem** or **metaliized*** filament lamp represents the result of efforts to better the carbon filament. It was found that a carbon filament lamp, which operates at 3.5 or 4.0 watts per candle under normal conditions could be forced to operate at a very much less specific consumption for a short time by increasing the voltage. The problem was to produce a carbon filament of better quality, more durable, and of a higher volatilization point so that it could withstand the much higher temperature, necessary to give a higher efficiency, without undue deterioration. The graphitized filament is the outcome of investigation along this line of reasoning and

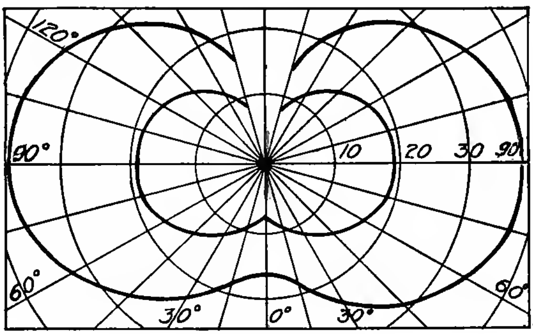


FIG. 33.

was developed by Mr. Whitney of the General Electric Company. It made possible the production of a 2.5-watt carbon lamp on a commercial basis and with a life comparable with the ordinary 3.1-watt lamp.

This lamp offers increase of refractiveness sufficient to operate at a temperature of about 1600 degrees centigrade. The graphitized filament is produced by subjecting the ordinary carbon filament to the temperature of boiling carbon in an electric furnace, or from the raw, untreated

* One should not be misled by this name to think that the filament has been treated with a metal. Only its appearance is metallic. It would be more suitable to call it "graphitized."

filament, which is first given the graphitizing process in the electric furnace, then removed and treated with the ordinary hydro-carbon process, after which it is again graphitized by means of the furnace. The high temperature of the furnace removes the ash residue and drives off the hydro-carbon contained in the filament, leaving the hard metallic like filament. It is evident that the graphitized filament can be used in any type of incandescent lamp bulb and can be mounted in any of the existing shapes similar to the carbon filaments. The distribution curves of light from this lamp resemble those from the same style carbon lamp as can be verified from Fig. 33. Curve *a* shows the distribution of light in a vertical plane, for 20-candle-power, 50-watt, oval anchored filament lamp; and curve *b* refers to the same type of lamp but of double the candle-power and specific consumption.

By this method of treating carbon filaments, lamps of 2.5 watts per candle-power are made, in sizes from 50 to 250 watts and from 20 to 100 candle-power, having a life of 450 hours to the slashing point. These lamps made by the members of the National Electric Lamp Association have a triple rating, *i.e.*, 114, 112, 110, volts. The following table* will show the makers claims as to the candle-power, life, and specific consumption of a lamp so rated when burned at those voltages. The lamp is a 50-watt Gem rated 114, 112, 110, volts.

Circuit voltage	Total watts	Mean horizontal c-p.	Watts per c-p.	Mean spher. c-p	Reduct. fact.	End c-p.	Useful hours	Life c p-hr.
Highest rating	50.0	20.0	2.5	16.5	82.5	8.1	450	8,330
Mean "	48.5	18.3	2.65	15.1	82.5	7.4	640	10,840
Lowest "	47.3	16.7	2.83	13.84	82.5	6.8	940	14,530

From this table it is seen that 2.5 watts per candle is about as high an efficiency as it is possible to obtain and at the same time have a consistent length of life, all attempts to add more refractory substances to the carbon filament

*Bulletin of the National Electric Lamp Association.

have failed, consequently, since the light emitted is proportional to the fifth power of the absolute temperature of the filament, and that further increase in temperature is the obvious method of producing greater economy, it is natural that the inventors should look for some substance to replace carbon and remain stable at high temperatures.

The **Helion lamp** represents a compromise between the carbon filament and the metallic filament lamps. The filament consists of a core of carbon of very small cross-section, mounted in the usual way and connected as for the ordinary flashing process of a carbon filament. Instead of a hydro-carbon gas, a gaseous compound containing silicon is inserted into the treating jar and deposited upon the filament process. At first the metal appears to enter the pores of the carbon, but as the process is continued the filament takes on a surface deposit. With this surface deposit the emissivity of the filament increases greatly and the color of the light changes from the characteristic color of the carbon lamp to a much whiter light with practically no change in temperature. When the desired resistance is obtained the deposit is stopped and the filament is ready for mounting in the bulb.

The filament is strong, can be burned in any position, and will withstand much higher temperatures than the carbon filament without softening or sagging. In fact, it is claimed that an excess voltage usually destroys the glass tube or the leading in wires before causing any damage to the filament. Results of tests indicate that the decrease in candle-power during its life is very small, and that a specific consumption of one watt per candle seems practicable in the lamps of larger sizes. Tests conducted at the Electrical Testing Laboratories* show the relation between the watts per candle-power and temperature as compared with a 3.5-watt carbon lamp. The temperature was taken by means of a Fey absorption pyrometer and the following results obtained:

* *Electrical Review,* 1907

Temperature centigrade	Watts per candle-power	
	Helion	Carbon
1,400	3.25	6.6
1,500	2.25	3.7
1,510	2.15	3.5
1,600	1.50	2.2

The temperature coefficient of resistivity of the Helion filament has been found to be negative up to 1,350 degrees centigrade when it changes and from there on possesses a decidedly positive characteristic; thus the lamp embodies the desirable properties of the carbon at starting and of the metallic filament lamp under operation.

The presence of blue rays in the light from a Helion lamp gives an illumination very closely resembling day light, which with its other commendable qualities must insure it a recognized place among incandescent luminants.

The **metallic filament lamps:**—There has been a great amount of investigation and study of the rare metals for the purpose of obtaining a substance to replace carbon in the manufacture of incandescent lamps and one able to withstand temperatures necessary to increase the efficiency of the lamp beyond that possible to obtain from the carbon filament. The results have appeared in lamps employing tantalum, tungsten, osmium, and a number of other rare metals. These lamps are proving very satisfactory and indicate a general revolution in incandescent lighting. The melting point in degrees centigrade, the specific gravity, and the atomic weight of some of the metals, are shown on the following page.

The **tantalum lamp** was invented by Dr. Bolton, chemist for Siemens & Halske, who discovered the peculiarities of tantalum and the methods of obtaining the pure metal.

The tantalum for commercial purposes is obtained from two groups of ore, namely, tantalite and columbite. The tantalite ores, found principally in Australia and Scandanavia, contain tantalate of iron and of manganese; while the columbite ores, first found in New England, contain, besides tantalite, mobale of iron and of manganese. From these ores, tantalum is first separated as tantalitic acid, converted into a double flouride of tantalite and potassium from which tantalum is derived as a pure metal. A new process for producing pure ductile tantalum consists in

Metal	Melting Point	Spec. gravity	Atom wt.	Metal	Melting Point	Spec. grav.	Atom wt.
Tungsten...	3080	19.1	184	Uranium...	800	18.7	240
Carbon.....	3000	2.1	12	Calcium....	800	1.6	40
Titanium...	3000	3.54	48	Neodymium	800	6.9	142
Tantalum..	2900	12.8	183	Lanthanium	800	6.1	138
Osmium....	2500	22.5	191	Aluminum..	657	2.6	27
Ruthenium.	2000	12.2	103	Magnesium.	630	1.78	24
Iridium....	2000	22.4	193	Antimony..	630	6.7	120
Rhodium...	1900	12.1	104	Cerium.....	623	7.04	140
Platinum...	1775	21.5	196	Arsenic	500	5.7	75
Vanadium..	1680	5.8	51	Tellurium..	450	6.3	126
Cobalt.....	1530	8.6	59	Zinc.......	419	7.1	65
Chronium..	1515	6.9	52	Lead.......	326	11.3	206
Zirconium.	1500	4.1	90	Cadmium...	320	8.6	112
Palladium..	1500	1.4	106	Thallium...	301	11.8	204
Nickel.....	1500	8.7	59	Bismuth ...	268	9.8	208
Iron.......	1400	7.8	56	Tin........	232	7.2	118
Boron......	1300	2.5	11	Selenium...	217	4.8	79
Manganese.	1245	7.5	55	Lythium...	186	0.59	7
Silicon.....	1200	2.3	28	Sulphur....	114	2.07	32
Gold.......	1065	19.3	198	Iodine	114	4.99	127
Copper.....	1055	8.9	63	Sodium....	96	0.97	23
Silver......	960	10.5	108	Potassium..	62.5	0.87	39
Germanium	900	5.5	72	Rubidium..	39	1.5	85.5
Beryllium..	900	1.64	9	Caesium ...	27	2.36	133
Strontium..	900	2.5	87	Mercury....	—39	13.6	200
Barium....	850	3.75	137				

heating in a vacuum above its melting point tantalum containing or combined with hydrogen, which is obtained by heating a mixture of tantalum chloride vapor and hydrogen. The vacuum is necessary in order that the tantalum may not absorb foreign matter from the atmosphere.

Tantalum is very heavy, having a specific gravity of 12.8. It has a gray metallic luster and melts at 2750 to 2900 degrees centigrade. Its resistance, like that of all metallic filament lamps, increases with the rise of temperature; it having 0.165 ohms per square millimeter at room temperature and 0.85 ohms at illuminating temperature or 0.234 per cent. rise per degree centigrade. When cold the tensile strength of tantalum is greater than that of steel—about 59 tons per square inch—but when hot it becomes soft and after burning a few hundred hours is easily broken. Tantalum can be hammered into sheets under a steam hammer by first heating it to a red heat, and after much hammering it becomes so hard as to resist a diamond bore.

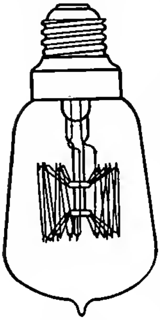


FIG. 34.

The diameter of the tantalum filament is from 0.05 millimeters to 0.035 millimeters. A 25-candle-power, 110-volt lamp requires a filament 65 centimeters long and weighing 0.022 grams hence one pound of tantalum will make about 20,000 lamps. The quality of the material and the great length of the filament are responsible for the shape and manner in which the filament is supported in the bulb. The General Electric Company has found means of increasing the resistance of tantalum so that a filament of greater cross-section or of shorter length can be used in incandescent lamps. The process consists in heating for a short time, a wire of pure tantalum in an atmosphere of nitrogen at 15 millimeters pressure. It is supposed that tantalum nitride is formed, but the practical result is that a filament having resistance of 65 ohms before treating has 240 ohms after treating and can be operated at a temperature equal to that of the ordinary tantalum filament. The only disadvantage presented by this filament lies in its extreme brittleness.

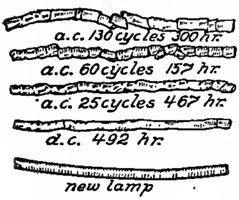


FIG. 35.

The appearance of the filament in the bulb can be seen from Fig. 34, it is supported by wires fused in and supported by a glass tube as shown. In Fig. 35 is an enlarged section of a filament, new, and when used on direct and alternating current circuits. This lamp is essentially a direct-current lamp. It has a shorter life and is less satisfactory on alternating current circuits.

A microscopic examination of the filament after burning on alternating circuits of different frequencies is very interesting. The new filament is smooth and has a polished surface; it becomes less regular on direct current in the course of time as shown in Fig. 35; on 25 cycles the irregularity is much more marked and a joint structure shows

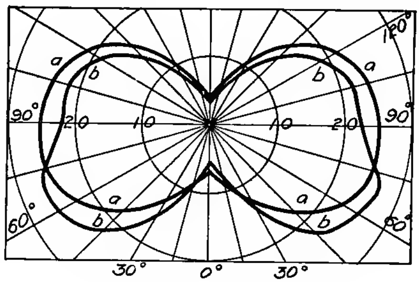


FIG. 36.

up, which at higher frequencies gives the filament the appearance of having been made up of small sections. The reason for this is obscure.

A rupture in a tantalum filament will often repair itself, the free end of the filament will cross with another portion of the filament and the lamp will continue to burn. A joint of this kind may result in a very strong weld and not necessarily make a point of special weakness in the filament.

The candle-power curve of the tantalum lamp in a horizontal plane must necessarily be a circle, in a vertical plane the value of the intensity of light plotted in polar coordinates (Fig. 36) gives a cirele on either side of the lamp.

if it be new. This curve changes with the life of the lamp, curve *b* showing the distribution of light from an old lamp. This change in the vertical distribution may be attributed to two causes: first, the deposit of black material around the sides of the bulb, and secondly, the change in the surface of the filament caused by service.

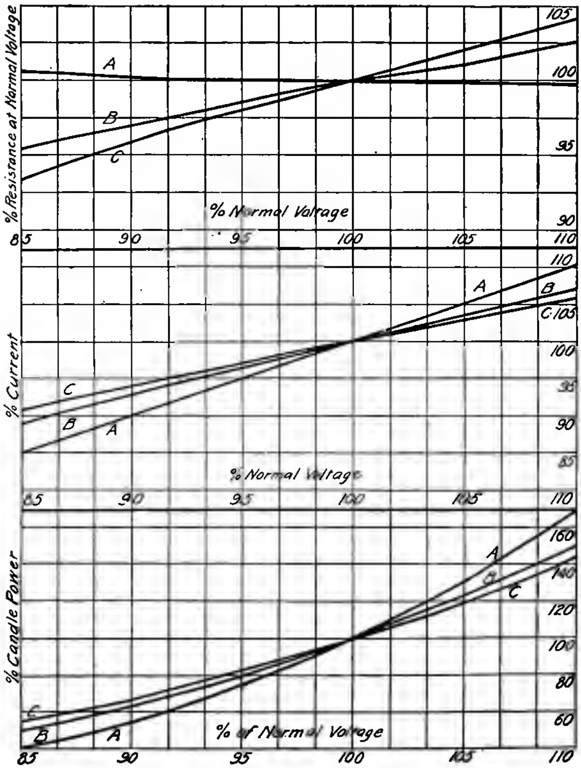
The light from the tantalum lamp is much whiter than that from the carbon filament, due to the much higher temperature at which it operates.

The life performance of a 25-candle-power lamp can be seen from the following table, which represents the characteristic features of this class of lamps.

Life hr.	Hor. c-p.	Current amp.	Watts per c-p.
0	19.8	0.391	2.17
25	23.6	0.400	1.87
50	23.1	0.400	1.90
125	22.3	0.401	1.98
225	22.4	0.400	1.96
350	22.3	0.400	1.97
450	22.2	0.400	1.98
550	21.2	0.395	2.05
650	19.6	0.392	2.20

The following curves show some of the characteristics of the lamp thus far described. Fig. 37 shows the variation of resistance with voltage; Fig. 38, current with voltage; Fig. 39, candle-power with voltage; Fig. 40 the typical life curves of carbon, graphitized, and tantalum lamps.

The **tungsten lamp.** The relation of tungsten to the manufacture of certain qualities of steel has been known for many years, but not until recently has its use been extended to the production of incandescent lamps. The discovery of its illuminating values has made possible an incandescent lamp comparable with the flaming arc and the vapor lamps in efficiency. Tungsten is obtainable in the form of a fire powder. It is not ductile, consequently it cannot be drawn into fine wires for filaments as is tantalum; it is fusible only at very high temperatures and at those temperatures combines readily with oxygen and with carbon. These peculiarities make the manufacture of the filament a difficult problem, with the result that there are several different processes of producing the filament of the tungsten lamp.



Figs. 37, 38 and 39.

It was discovered that the oxychlorides of tungsten and molybdenum are reduced by hydrogen at a red heat, forming the metal, hydrochloric acid, and water. If, therefore, a hot carbon filament is placed in an atmosphere of tungsten oxychloride mixed with an excess of hydrogen, the reduced tungsten will be deposited on the filament forming a tungsten coating on a carbon core. If, on the other hand, there is but very little hydrogen present, then the carbon filament, when heated, will gradually change to one of pure tungsten. It is explained that the carbon combines with the oxygen of the oxychloride, forming carbon monoxide while the chlorine is reduced by the hydrogen to hydrochloric acid, and tungsten replaces the carbon. The condition of complete displacement of the carbon by tungsten requires that there shall be an excess of oxychloride vapor, a very little hydrogen, and a high temperature. At low temperatures and with excess of hydrogen, carbon takes no part in the reaction. Molybdenum reacts similar to tungsten.

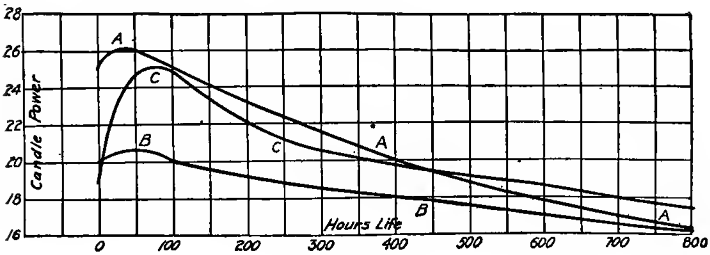


FIG. 40.

Dr. Kuzel has a method of making filaments from amorphous powder without the help of an organic binding substance. He employes the refractory metals in their colloidal condition, either as hydrosol, organsol, gel, or as a colloidal suspension. These metals include chromium, manganese, molybdenum, uranium, tungsten, zirconium, platinum, osmium, iridium, vanadium, tantalum, niobium, titanium, thorium, and ruthenium. These metals are obtained in their colloidal form by causing an electric arc, under water, between terminals composed of the metal. The colloidal solution, when it has attained the proper consistency, is squirted through a die into filaments. After being dried they are converted from the colloidal to the crystalline condition by passing electricity through them. In this way the filament is produced without introducing any carbon which, if present, would form tungsten carbide, a compound very detrimental to the quality of the tungsten filament.

Another process is the substitution process of Dr. Just and Mr. Hanaman. A very fine carbon filament is heated in an atmosphere of a chloride of tungsten and hydrogen. The hydrogen acts as the reducing agent and tungsten is deposited on the filament. By heating the filament by means of a current it is converted into tungsten carbide. The carbon is then removed by heating the filament in an atmosphere of steam and hydrogen; the steam being decomposed, oxidizes the carbon of the carbide. Any tungsten oxidized by this method is reduced by the hydrogen.

Another process of manufacturing the tungsten filament (Welsbach's method) involves the squirting of a paste consisting of the powdered tungsten with an organic binder. After the filament is dried and hardened the organic matter is removed leaving the tungsten. It has been found possible also to use paraffin for a binder, which can be removed very easily by heating, and metallic alloys having low melting temperatures may be employed to bind the tungsten, the foreign metals being removed by heat. British patents cover several methods of preparing tungsten filaments. In one of these tungsten is mixed with an amalgam of mercury and cadmium. The mass is squirted into filaments and the amalgam expelled by heating the filament in a vacuum or in an atmosphere of hydrogen. In another the amalgam is replaced by an alloy of bismuth and cadmium.

A process of preventing blackening of the bulb during the prolonged exhaustion required for the metallic filament lamps consists in maintaining an atmosphere of phosphorus vapor in the bulb, the temperature being such that no phosphorus is deposited. This is accomplished by painting the filament leads and the glass stem with finely divided red phosphorus mixed with alcohol or ether.

The tungsten filament has all the ordinary properties of wires of pure metals. It has a temperature coefficient of resistivity of 0.438 per cent. per degree centigrade. Its resistance is low, which requires that the filament be either of very small cross-section or of considerable length, in order to meet the requirements of an incandescent lamp. A compromise between the two is taken. When incandescent the tungsten filament is very soft and the loops require supports to keep them in position. These supports consist of wires fused in the stem of the lamp and coiled around the ends of the loops. More recent lamps are being constructed with the filament supported in a manner similar to that of the tantalum lamp. The filament is passed through loops in the supported wires as shown in the figure and being thus made can be burned in any position.

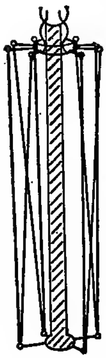


Fig. 41.

The peculiarities of the tungsten filament indicate a tendency toward lamps of higher candle-power and the properties are such that it seems well adapted for the production of incandescent lamps for the series system of street lighting, where lamps of comparatively low resistance and high current capacity are most desirable.

The chief disadvantage of this lamp lies in the extreme fragility of the filament, it is likely to become damaged from constant vibration or from carelessness in handling, but when properly mounted and the necessary care exercised a long life is obtained and the high efficiency of the lamp and the white color of the light more than compensate for the initial cost.

The color of the light from the tungsten lamp is whiter than that from the tantalum and much whiter than that from the carbon lamp; it resembles quite closely, the light from an acetylene flame. A photometrical experiment comparing a tantalum and a tungsten lamp with a carbon lamp consuming 3.1 watts per candle-power shows this difference in color. The lamps were photometered against the carbon lamp directly and then with a red, green, and blue glass interposed between the eye and the eye-piece of the photometer. The intensities so measured expressed in per cent. of the intensities measured without the colored glass are given in the following table.

	Tantalum lamp	Tungsten lamp
	per cent.	per cent.
Normal light................	100	100
Red "	90.5	83.0
Green "	100.3	101.8
Blue "	109.2	126.5

The increased whiteness of the light from a tungsten lamp may theoretically be due either to a higher tempera-

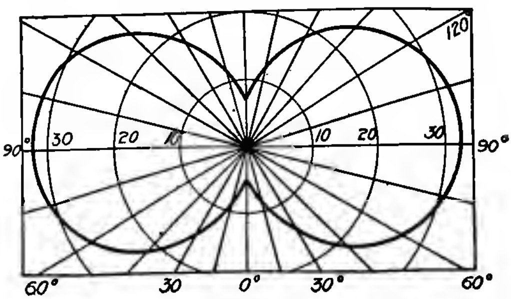


Fig. 42.

ture of the filament or to the greater selective radiation by the filament. Although this is due to some extent to the latter effect, the principle cause lies in the high temperature at which the lamps operate.

The positive temperature coefficient of resistivity of the metallic filaments gives considerable inherent regulation to this type of lamp. On closing the circuit the current is several times greater than it is a fraction of a second later when the filament has reached incandescence. The result is that the candle-power varies less with variations in voltage and the service is more satisfactory than with lamps having a negative coefficient. The following table shows this effect for a 5 per cent. increase in voltage for the lamps studied thus far:

Type of lamp	Candle-power per cent.	Watts per candle per cent.
Carbon filament.....	+30	—15
Graphitized "	+27	—13
Tantalum "	+22	—11
Tungsten "	+20	—10

The distribution of light around a tungsten lamp must be nearly uniform in a horizontal plane due to the shape of

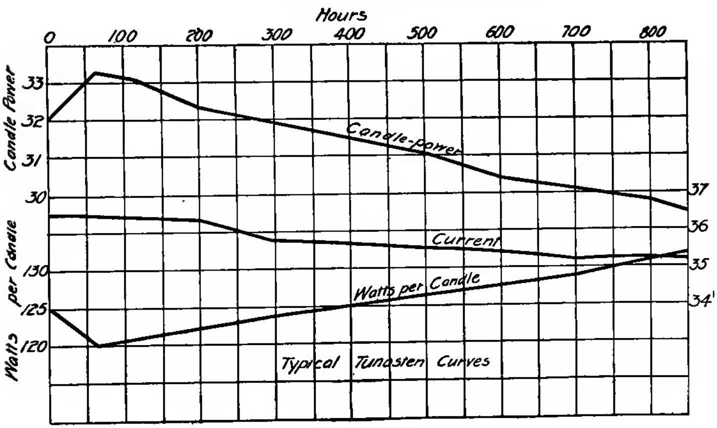


FIG. 43.

the filament, while in a vertical plane the intensity of light plotted to polar coördinates is shown in Fig. 42.

Ruptures in the tungsten filament will often repair themselves but the junction is not so secure as in the case of the tantalum lamp and is apt to break apart. These ruptures which become repaired are responsible for the irregularities in the life curves of the metallic filament lamps not seen in the life curves of the carbon lamps.

The life curves of a typical tungsten lamp are shown in Fig. 43 and the variation in candle-power, resistance, and consumption, with voltage together with a carbon lamp may be observed from Fig. 44.

In the table on the following page data are given on the standard lamps manufactured by the National Electric Lamp Association.

These results are approximately the same on alternating current as on direct, except those for the tantalum lamp. The first two lines on the tantalum lamp give results when the lamp is supplied with direct current and the other two when supplied with alternating current.

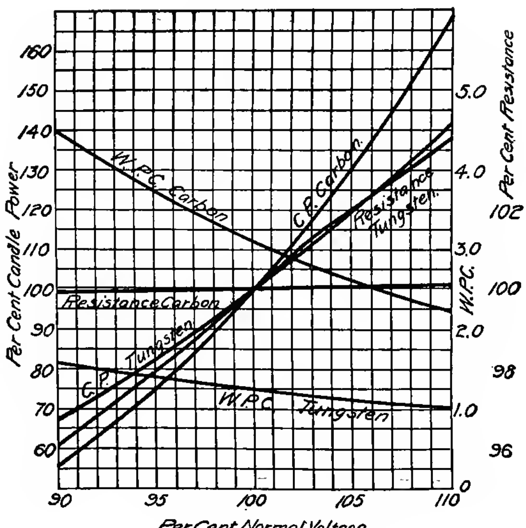


FIG. 44.

The tungsten lamp is made in European countries under the name of the osram, osmin, wolfram, and others the principle difference being in the method of preparing the filament.

The **osram lamp**, made in Germany, was brought before the public in 1905, and has been manufactured on a large scale ever since that time. The specific consumption of the lamp is about 1.25 watts per candle-power and it burns

Type of lamp.	Mean horizontal candle-power.	Nominal watts per candle-power.	Actual watts per candle-power.	Total watts.	Hours total life	Kilowatt-hours consumed during life.	Cost of lamp in cents.	Renewals for 1000 hours in cents.	The combined cost of energy and lamp renewals for 1000 hours when the cost of energy is 4, 8, and 12 cents per kilowatt-hour respectively.		
Carbon........	16	3.1	3.10	49.6	590	29.3	16.0	27.2	2.26	4.24	6.22
	16	3.5	3.57	56.0	1160	65.0	16.0	13.8	2.38	4.62	6.86
	16	4.0	4.00	64.0	2360	151.0	16.0	6.8	2.63	5.19	7.75
	20	3.0	3.04	60.8	520	31.6	24.0	36.8	2.74	5.17	7.60
	20	3.5	3.48	69.6	1040	72.4	24.0	15.4	2.94	5.72	8.51
	20	4.0	4.17	83.4	3280	273.6	24.0	7.3	3.41	6.74	10.08
	32	3.1	3.1	99.2	595	153.4	24.0	40.4	4.37	8.34	12.31
	32	3.5	3.57	114.2	1200	137.1	24.0	20.0	4.77	9.34	13.91
Graphitized....	20	2.5	2.50	50.0	560	28.0	20.0	36.0	2.36	4.36	6.36
	18.3	2.5	2.65	48.5	800	38.8	20.0	25.0	2.19	4.14	6.07
	16.7	2.5	2.83	47.3	1175	55.6	20.0	17.0	2.06	3 95	5.85
	40	2.5	2.5	100.0	575	57.5	30.4	53.0	4.53	8.53	12.53
	36.7	2.5	2.65	97.0	812	87.7	30.4	37.0	4.25	8.13	12.01
	33.5	2.5	2.83	94.0	1200	113.0	30.4	25.0	4.01	7.77	11.53
	50	2.5	2.5	125.0	560	70.0	38.8	69.0	5.69	10.69	15.69
	45.9	2.5	2.65	131.3	800	97.3	38.8	48.0	5.32	10.18	15.04
	41.8	2.5	2.83	117.4	1175	138.0	38.8	33.0	5.03	9.72	14.42
	75	2.5	2.50	187.5	560	105.0	55.2	98.0	8.50	16.00	23.50
	68.7	2.5	2.65	182.0	800	145.0	55.2	69.0	7 99	15.27	22.55
	62.7	2.5	2.83	176.0	1175	206.5	55.2	47.0	7.51	14.55	21.59
	100	2.5	2.5	250.0	560	140.0	68.0	121.0	11.21	21.21	31.21
	91.7	2.5	2.65	242.5	800	194.0	68.0	85.	10.55	20.25	29 95
	83.5	2.5	2.83	234.8	1175	276.0	68.0	58.0	9.97	19.36	28.76
Tantalum	20	2.0	2.0	40.0	1400	56.0	48.0	24.3	1.94	3.54	5.14
	40	2.0	2.0	80.0	1600	128.0	68.0	42.5	3.62	6.83	10.03
A.C	20	2.0	2.0	40.0	600	24.0	48.0	80.0	2.40	4.00	5.60
	40	2.0	2.0	80.0	900	72.0	68.0	75.6	3.96	7.16	10.36
Tungsten......	32	1.25	1.25	10.0	1000	40.0	120.0	120.0	2.80	4.40	6.00
	48	1.25	1.25	60.0	1000	60.0	140.0	140.0	3.80	6.20	8.60

about 1000 hours with little decrease in candle-power The average results of Reichsanstalt tests on eight 25-candle-power and eight 28-candle-power lamps for from 111 to 117 volts showed the following results.

Time in hours of life....	0	200	400	700	1000
25-candle-power lamp..	25.0	26.2	25.2	24.3	23.8
Watts per candle-power	1.28	1.21	1.24	1.30	1.31
28-candle-power lamp..	28.2	29.8	29.0	27.7	26.5
Watts per candle-power	1.29	1.21	1.24	1.30	1.31

The maximum and minimum decrease for the 25-candle-power lamps were 11.4 per cent. and 4.2 per cent. respectively while the 28-candle-power lamps showed a 6.1 per cent. maximum and a 0.6 per cent. minimum. Eleven of the sixteen lamps were uninjured by the 1000 hours service.

The osram lamp yields the same results on alternating current as on direct current, as do all tungsten lamps. It has been made to operate successfully on voltages as high as 220 volts and giving as high as 200 candle-power. Lamps giving 16 candle-power on 70 volts and bearing a similar ratio up to 200 candle-power on 220 volts yield one Hefner candle per watt with a satisfactory life. A 110 volt lamp giving only 16 candle-power is not so efficient.

It has been stated that the filament of the osram lamp consists of a mixture of tungsten and osmium, finely divided and made into a paste with some organic binding material, and the filament formed by the squirting process.

The **osmin lamp** is the form of the tungsten lamp manufactured in Vienna. It consists essentially of a squirted filament of powdered tungsten with an organic binder. The carbon is removed by heating the filament in an atmosphere of steam and hydrogen. The finely divided powder is obtained by Dr. Kuzel's colloidal process. These lamps show remarkable life and high efficiency; two, 30-volt, 11.5-candle-power lamps consumed 1.25 watts per candle and one burned for 3500 hours with only 10 per cent. decrease in candle-power. A test of three, 55-volt, 44-candle-power lamps showed a life of 1200 hours with a decrease of

14 per cent. in candle-power. Other tests of this lamp have showed up equally well.

The **sirius colloid lamp** is made by Dr. Kuzel's colloidal process. The makers claim a specific consumption of 1.15 watts per candle for 1000 hours and guarantee a life of 1000 hours when burned at this consumption. This lamp is made in three standard sizes, 25, 50 and 100 candle-power.

The relation of the voltage to the candle-power and watts per candle-power are given below:

Per cent. normal voltage......	100	150	200	250
Per cent. normal candle-power.	100	400	1000	1900
Watts per candle-power.......	1.15	0.52	0.3	0.23

The **"Z" lamp** is still another tungsten lamp. The process by which it is manufactured involves the squirting of a paste consisting of finely divided tungsten and an organic binding material, but it differs from the others in the method of removing the organic matter from the filament.

The **zircon-wolfram lamp** made of a mixture of zirconium and tungsten (German " Wolfram ") is a metallic filament lamp which can be made suitable for 200 to 220 volts pressure. It is the invention of Dr. Zernig of Berlin, who has not made public the exact process of obtaining the filament. It is supposed that hydrogenous combinations of the metals are reduced to such a condition that the filament can be made by the process of squirting and the filament finished by one of the processes previously described. The lamps behave the same on alternating current as on direct, it is not fragile, and has a specific consumption of about 1.4 watts per candle-power. Its life is about the same as that of the tungsten lamp, and it is made for 16 candle-power on 100 volts and 32 candle-power on 200 volts.

The **osmium lamp:** Welsbach was the first to suggest osmium for incandescent lamps. This metal is extremely brittle and can be made into filaments only by mixing the finely divided particles with an organic binding substance. The binding material is carbonized in the usual way and the filaments are heated to a white heat in a reducing atmosphere which removes the carbon.

In addition to the fact that these lamps are only suitable for low voltages, there is the further question of obtaining the necessary amount of osmium, which, until recently, was not much used, and that obtained by purifying platinum supplied the demand. Welsbach, before publishing his invention, bought up all the known sources of osmium. The manufacturing companies buy back their old lamps from which they get much of their raw material.

Dr. Blau obtained osmium filaments by placing carbon filaments in a vapor of osmium tetroxide, from which the reducing gases were excluded. The osmium tetroxide was reduced to a metallic condition, replacing the carbon which volatilized in the course of reaction. Osmium filaments are not commercially made by this process however, still it is possible by this method to obtain 32 candle-power lamps for 110 volt circuits, while filaments of suitable dimensions cannot be constructed by the paste process.

The filaments of the osmium lamp cannot be made of great length. When hot the filament is soft and requires supports in order to keep it in its proper position. These supports are made of 10 parts by weight of pure thorium and one part by weight of magnesia, finely divided and made into a paste with an organic binder after which, they are formed, dried, and the organic matter driven off. The temperature coefficient of resistivity of the osmium filaments is +0.372 per cent. per degree centigrade. This lamp is guaranteed for 500 hours. It is liable to damage from vibration or shocks, and guarding these it is capable of burning several thousand hours. When exposed to the air, osmium gives off a volatile oxide which is highly poisonous and has resulted in loss of eyesight to those exposed, consequently a cracked lamp might be a source of danger.

Tests on six 35-volt, 16-candle-power and six 35-volt, 25-candle-power lamps showed the following results:

Hours life	16-candle-power lamps		25-candle-power lamps	
	Candle-power	Watts per c-p.	Candle-power	Watts per c-p.
0	15.1	1.68	22.25	1.65
400	17.3	1.46	24.10	1.53
2100	15.6	1.58	22.6	1.61

Average life of the 12 lamps, 1985 hours.

The average specific consumption of the 16-candle-power lamps throughout their life was 1.6 watts per candle.

The average specific consumption of the 25-candle-power lamps was 1.8 watts per candle.

Several forms of **zirconium lamps** have been made. The hydrides or nitrides of zirconium are used in combination with an organic binding material. The hydride is obtained by reducing zirconia by means of magnesium in a current of hydrogen, if an excess of magnesium is used the product is said to be ZrH_4. The hydride, after being treated with dilute hydrochloric acid to remove the magnesia, is dried and made into a paste by means of the organic binding material. The filament is then forced through a die and dried in an atmosphere of hydrogen at a temperature of 300 degrees centigrade. After being mounted the filament must be heated in order to make it conduct. They can then be made incandescent by the passage of a current and the formation of a carbide takes place. Hydrogen is then passed into the bulb and the filament becomes hard and metallic. These lamps take about two watts per candle-power.

The **zirconium-carbon lamp** is made by heating an ordinary carbon filament in a vapor of some volatile zirconium compound. This lamp shows a slight improvement over the carbon filament lamp.

Iridium has been used for making filaments, the process being similar to those of the osmium and zirconium lamps. Iridium in the form of powder is mixed with a binding medium, squirted into filaments which are heated until the binding material is driven off and the iridium particles frit together. Because of the low voltage of the lamp and the scarcity of the iridium this type of lamp is unlikely to be of much commercial importance.

The **titanium lamp** was brought before the public in 1901 by Mr. Walker. The filament was made of the carbide of titanium prepared in an electric furnace. The filament was much shorter than that of the carbon lamp and both strong and elastic. Filaments were made to withstand 500 volts but this necessitated a larger bulb and trouble was experienced due to the leakage across the base of the lamp which became sufficient to rupture the filament in case of an incomplete vacuum. This leakage was prevented by placing a double glass insulator between the filaments. This glass insulator was allowed to extend back through the base of the lamp between the leading-in wires in order to prevent leakage in that part of the lamp. It was found that this insulation between the filaments also increased the life of the lamp. The report of tests of these lamps showed an initial specific consumption of 2.53 watts per candle-power, 2.84 watts per candle at the end of 500 hours and 3.35 watts per candle at the end of 1000 hours.

The **cazin lamp** had its origin prior to any of the metallic filament lamps previously mentioned. The inventor seems to have withheld his discovery to such an extent that the lamp was not produced in great numbers. The composition of the filament is a secret. It possesses a higher resistance than any of the pure metal filaments, the reason for which it is reasonable to suppose results from its being an alloy. This filament produces a brilliant white light and it is claimed to consume only 1.7 watts per candle-power and to have an average life of 600 hours.

The **film lamp,** developed by Messrs. Parker and Clark consists of a quartz tube with a highly refractory conducting film lining the bore of the tube and making electrical connections at the ends. One of the interesting features of this lamp is that the quartz tube permits the passage of the short wave length or ultra-violet rays of light of which there is a great quantity. It was found that the efficiency of the lamp could be increased by coating the surface of the tube with thorium oxide which under the influence of the heat and the ultra-violet rays glowed with the characteristic light of a Welsbach mantle. This lamp consumed about 2.5 watts per candle-power. The attention of the War Department was attracted to this lamp because with the heavy quartz tube and since a vacuum is not necessary it seemed well adapted to withstand violent concussions which are destructive to the ordinary filament lamp.

The **Nernst lamp.** In the development of this lamp, Dr. Nernst assumed that none of the metals could replace carbon in the incandescent lamp and therefore turned his attention to electrolytic conductors. He found that magnesium, zirconium, thorium, yttrium, and other rare earths became good conductors when heated, and by means of a suitable mixture of the oxides of zirconium and yttrium, he was successful in overcoming the electrolytic effect produced by direct current, and in producing a "glower" capable of withstanding the temperature of incandescence without a vacuum.

The glowers are formed in small tubes and connections made to either end by means of small platinum wires. In the earlier stages of development these connections were made by winding the wire tightly around the glower, but it was found that the oxides showed a tendency to shrink away from the wire and cause poor contact, consequently, the ends of the glower were hollowed and a small particle of platinum fused into either end. To this small particle the platinum wire was joined without difficulty and this junction proved very satisfactory on alternating currents. The alternating current glower is vitrified and very strong while those designed for direct current are made as porous as possible in order to minimize the electrolytic effect. This difference in structure together with a slight electrolytic effect, makes necessary a different negative terminal in the direct current glower, this terminal consists of a band of several turns of platinum wire tightly wound around the material of the glower. Both terminals of all glowers are coated with some of the ground glower-material for the purpose of affording more perfect electrical connections and increasing the radiating surface, thus disposing of any additional heat due to the Peltier effect. The glower is electro-positive to the platinum; consequently the negative terminal will be at the lower temperature.

The development of the direct current Nernst lamp is of recent date and but comparatively few installations have as yet been made. Although the makers guarantee a life of only 500 hours, the reports from several installations show an average life of 900 hours.

The adjustment of the glower for a certain voltage is performed by holding it in an arc which causes the material to collect in globular form and creep along the cylindrical portion of the glower. When the glower has attained the proper dimensions it is removed from the arc. The progress of the operation is observed by means of an image thrown on a screen by a lens.

The material of which the glower is made requires heating before it will conduct electricity and produce a light, consequently it becomes necessary to employ an electric heater. This heater is mounted above and close to the glower and both are inclosed by a glass globe. This globe is not air-tight, as the Nernst lamp does not require a vacuum.

The upper part of the lamp contains the "ballast"—a small regulating resistance in series with the glower, and an automatic "cut-out," to throw the heater out of service after the glower has become incandescent.

In European countries the heaters are almost always coiled around the glowers, but this type of heater seems unpopular in this country and except in lamps for the series street lighting systems, a tube of porcelain wrapped with fine platinum wire and then covered with some non-conducting paste for protective purposes, has been adopted. One or more of these heaters are placed horizontally above the glower which is itself also in a horizontal position.

These heaters are in the circuit when the lamp is turned on, but as the glower heats up, the current through it actuates an electromagnet which is connected in series with the glower and which opens the heater circuit. The difficulties experienced from the leakage of electricity through the porcelain and the unequal expansion of the platinum and porcelain are overcome by using only a pure and soft grade of porcelain. The guaranteed life of the heater tube is 2500 hours. Numerous attempts have been made to do away with the matter of preliminary heating, but the fact remains and is the chief drawback to the universal adoption of the lamp.

In some cases as on ship-board where there might be uncertainty in the action of an automatic device, the heaters are connected by means of a third wire and switch in such a manner that after the lamp is lighted the switch can be opened and the heaters cut out, thus eliminating the necessity of an automatic cut-out.

The peculiar characteristic of the glower, which is shared to some extent by nearly all electrolytes, namely, a decided negative temperature coefficient of resistivity, necessitates the introduction of a compensating resistance which should have a large positive temperature coefficient of resistivity and thus prevent an excess of current from passing through the glower, fusing and destroying it.

Pure iron wire was found best adapted for the material of this resistance and it is mounted in a glass tube filled with an inert gas, preferably hydrogen, to prevent rust and deterioration. Since the temperature of this wire when in service, depends on the rate at which heat is conducted away from it, the final adjustment of the ballast can be accomplished by exhausting the tube. This is performed by placing the required size and length of wire in the tube and slowly exhausting the tube until the resistance of the wire, which is connected to an electric source of definite potential, allows the desired current to exist. The tube is then sealed and ready for use. The guaranteed life of the "ballast" is 1200 to 1500 hours.

The action of the lamp on closing the circuit and the resulting current-time curve are very interesting. When the switch is closed, the current falls rapidly due to the rise in temperature of the heater, then it rises as the glower becomes heated, to fall again suddenly as the heater is cut out and the lamp becomes luminous, hence it again rises above normal before becoming constant. This curve can be seen in Fig. 45.

The construction of a one glower lamp is shown in Fig. 46 and its connections in Fig. 47.

The humming which was noticeable in the older type of alternating current lamps and which was due to the lamina-

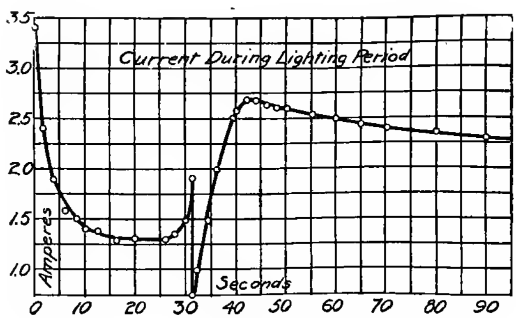


FIG. 45.

tions of the electromagnet, was overcome by so placing the bearings of the armature that its axis makes an acute angle with the direction of the force due to gravity and the force due to the electromagnet.

The multiple alternating lamps are made in five different sizes—one, two, three, four, and six-glower lamps, and for 110 and 220 volts. The 110-volt multiple-glower lamp has in addition a converter coil which receives energy at 110 volts and delivers it to the lamp at 220 volts. The 220-volt lamp operates at any voltage from 200 to 260 and the 110-volt lamp operates on any voltage from 100 to 120. The 110-volt single-glower lamp operates directly on 110-volt mains. The manufacturers claim that these lamps will successfully replace three, seven, ten, thirteen, and twenty 16-candle-power incandescent lamps respectively. The 110-watt lamp gives an illumination equal to five and one-half 16-candle-power lamps.

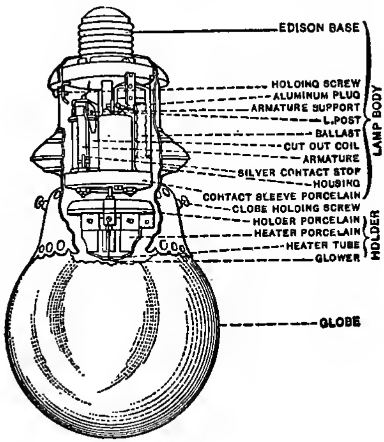


FIG. 46.

The direct-current lamps are made with one, two, and three glowers and give the same candle-power as the corresponding alternating-current type. They operate on even voltages from 200 to 240 volts. The adjustment for different voltage circuits is made on the holder and only requires the use of different glowers.

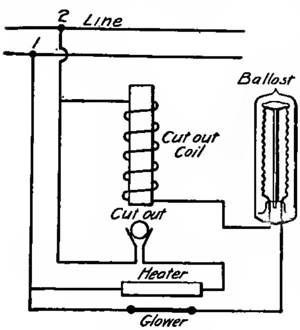


FIG. 47.

Lamps with two or more glowers show a higher efficiency than the single glower lamps due to the higher temperature resulting from the proximity of the illuminating sources.

Fig. 48 shows the arrangement of the parts of a three glower lamp and Fig. 49 the diagram of connections for the same lamp.

The engineers in developing the Nernst lamp made a careful study of light distribution. They came to the conclusion that the useful rays of light were those projected in a vertical direction while those in a horizontal direction

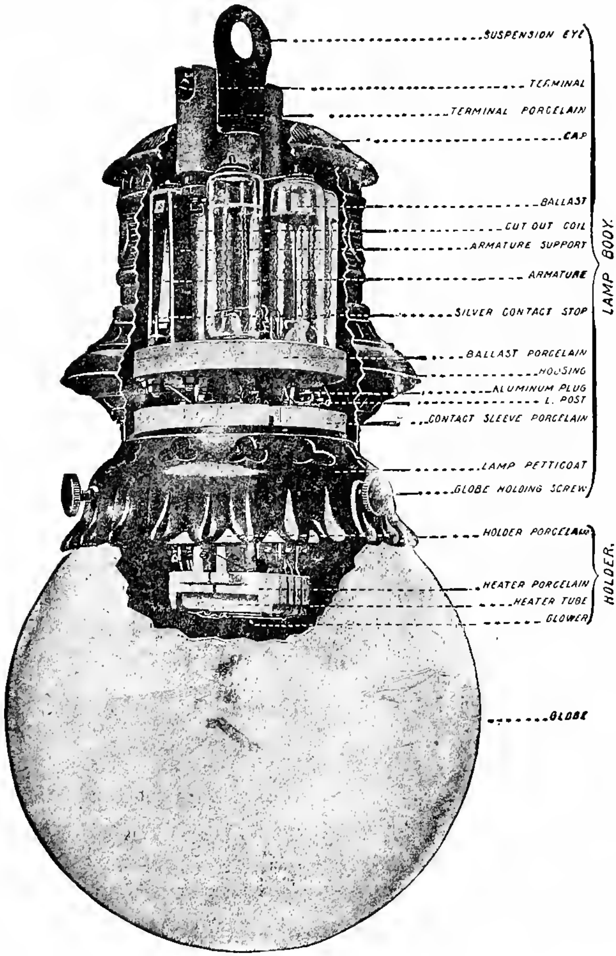


FIG. 48.

merely dazzled the observer, consequently the lamp was designed with this consideration in mind. Nearly all of the light from a Nernst lamp is in the lower hemisphere, hence no reflector is necessary. It is claimed by the makers of this lamp that it will give twice as much illumination for the same watts consumed as the average incandescent lamp.

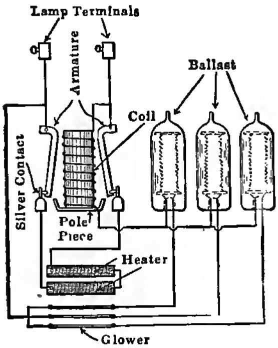


Fig. 49.

The distribution of light in a vertical plane from Nernst lamps having opalescent bowls and no reflectors is shown in Fig. 50. Curve *A* is for a 1-glower, 88-watt, 72-candle-power lamp; *B*, 2-glower, 176-watt, 147-candle-power lamp; *C*, 3-glower, 264 watt, 218-candle-power lamp; *D*, 4-glower, 352-watt, 290-candle-power lamp; *E*, 6-glower, 528-watt, 438-candle-power lamp. Fig. 51 shows the distribution of light from a 2, 3, 4, and 6-glower Nernst lamp, with a concentrating bell shade. These give 254, 392, 540, and 810-candle-power respectively as shown by curves *A*, *B*, *C*, *D*.

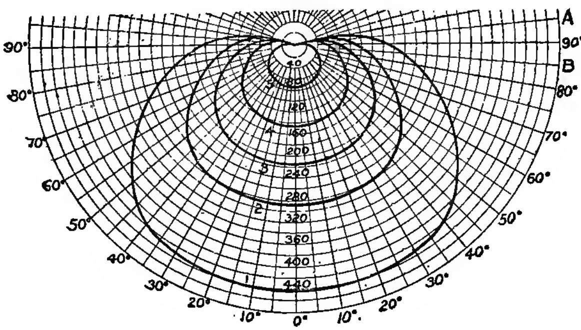


Fig. 50.

During the several years that the Nernst lamp has been on the market it has proven very satisfactory. It has been adopted for lighting some of the finest and largest buildings in the country. It possesses the advantage of being available in units of candle-power covering all ordinary requirements thus making it possible to furnish entire installations with light of the same color where otherwise it would be necessary to employ units of widely different color values as the arc and incandescent lamps.

Owing to the composition of the glower and the high temperature at which it operates, the light is of a brilliant white color and approaches daylight in appearance more nearly than any of the other incandescent illuminants.

The new lighting system installed in the dry-goods store of Marshall Field & Co. in Chicago in 1907 consisted in replacing 57,000 incandescent lamps with two and three-glower Nernst lamps. This lamp was the almost unani-

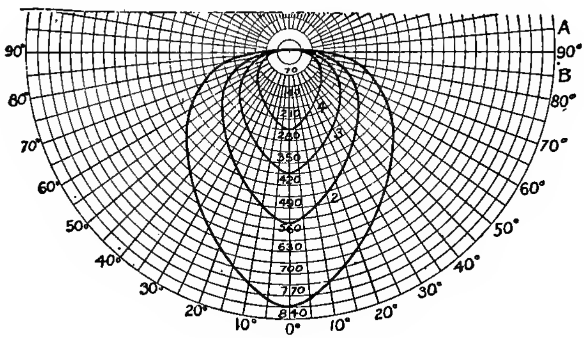


FIG. 51

mous choice of the 350 department managers of the company. Their choice was based primarily on the quality and amount of light supplied relative to the display of the goods in their departments although they were doubtless influenced by the results of engineering investigation and the desire of the management to have only one system of lighting. The intensity of illumination on the counters of the first floor of the building is from 4.5 to 5 foot-candles; on the second floor from 2.8 to 3 foot-candles; and 3.5 to 4 foot-candles in the basement.

The Nernst Lamp Company has developed a 110-watt lamp of high efficiency which fits the Edison screw base socket. It was designed to replace lamps of lower candle-power without the additional cost of fixtures. Its advantages as compared with the 88-watt unit are:

	110-watt lamp	88-watt lamp
Watts..........................	109	88
Mean Hemispherical c-p..........	79.4	40.2
Watts per mean hemispherical c-p.	1.37	2.19

This lamp gives a downward light of 115-candle-power and has a specific consumption of 0.96 watts per candle when equipped with a clear glass globe.

The life performance of a standard glower at constant consumption is shown in the following results:—

Hours life	Voltage glower	Per cent. voltage increase	Candle-power glower	Per cent. deprecia-tion
0	202	.00	44.5	.0
200	199	—1.49	43.5	2.2
400	202.6	0.30	41.4	7.0
600	206	2.13	38.9	12.6
800	210	3.96	36.5	18.0

The resistance of the glower constantly increases with age. This is supposed to be due to the change in its structure from an amorphous state of smooth chalk like appearance when new, to a rough chrystalline state which it assumes after a few hundred hours of life.

The relative merits of Nernst lamps equipped with sand blast globes, and alternating and direct-current enclosed arc lamps equipped with opal inner and clear outer globes, can be seen from the following data.*

	Nernst Lamps				Arc Lamps	
	Six-Glower	Four-Glower	Three-Glower	One-Glower	A.C. Multiple	D.C. Multiple
Voltage..................	220	220	220	220	110	110
Watts....................	521	349	263	88	417	539
Mean spherical c-p........	176.4	115	77.1	22.5	140	182
Mean hemispherical c-p....	297.2	189.1	124.5	36.3	167	239
Watts per mean spherical c-p.	2.95	3.03	3.45	3.92	3.02	2.96
Watts per mean hemispherical c-p................	1.76	1.84	2.11	2.43	2.53	2.25

* N. E. L. A. Transactions, 1905.

The average life performance of five four-glower lamps can be studied from the following data. The tests were made on 60 cycles, 226 volts, and the lamps were interrupted every three and one-half hours.*

Life	Mean spherical c-p.	Mean hemispherical c-p.	Watts	Mean spherical watts per c-p.	Mean hemispherical watts per c-p.
0	105.6	179	349	3.31	1.95
25	108.5	181	352	3.25	1.95
200	94.3	157	340	3.61	2.17
600	84.9	142	329	3.88	2.32
1000	84.4	140.5	319	3.78	2.27

During the test 12 of the 20 glowers had to be replaced by new glowers. No heaters burned out. A maintenance test run on six of the above type of lamps for 2250 hours on the same circuit showed the following results:—*

Duration of test in hours	2250
Number of four-glower lamps on test	6
Total number of glower hours	54000
Number of glower burnouts	34
" " heater "	8
" " ballast "	0
" " heater porcelains broken	1
Average glower life in hours	1600
" heater life (calculated)	3375

The effect of change in voltage on four-glower lamps is shown in the following table.

Volts	Current	Watts	Mean hemispherical c-p.	Watts per mean hemispherical c-p.
180	0.80	147	32.4	4.53
190	0.98	187	53.0	3.53
200	1.19	238	90.5	2.63
210	1.40	295	144	2.05
220	1.55	341	185	1.84
230	1.63	374	201	1.86
240	1.64	393	203	1.93
250	1.65	413	207	1.99
260	1.69	440	220	2.00

* N. E. L. A. Transactions, 1905.

The **series system** of street lighting with Nernst lamps involves the use of a series transformer of special design. This gives a characteristic on the secondary side which will permit the lamp to operate under normal conditions without undue strain and at the same time allow the transformer to remain in circuit if the lamp fails to give light. This peculiarity is accomplished by introducing into the magnetic circuit of the transformer, an air-gap, which prevents excessive heating of the iron when the secondary circuit is open. This also flattens the current-voltage characteristic on the secondary side; *i.e.*, on lighting, the voltage does not decrease too much, nor, when the heater is cut out does the voltage rise abnormally high.

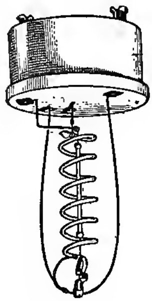


Fig. 52.

A feature of this system is the operation of the glowers without ballast, since the constant current primary maintains a constant current through the secondary and glower.

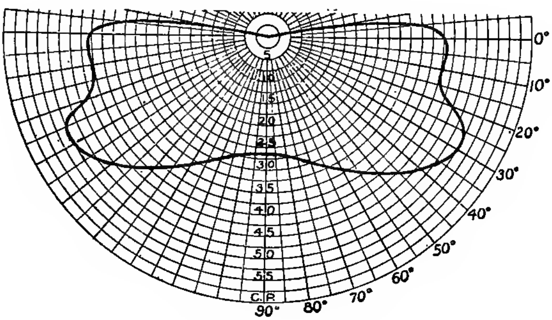


Fig. 53.

It will be seen that this increases the efficiency of the system. The glower of this type of lamp is placed in a vertical position (Fig. 52) and in center of the heater, which in this case consists of a platinum wire in the form of a helix and coated with porcelain. The light from a glower so placed will have its maximum value a little below the horizontal plane where it is most desirable for street lighting. This distribution in a vertical plane is shown in Fig. 53.

The cost of maintenance of a Nernst installation is stated as about 6 mils per kilowatt-hour, in which respect it compares favorably with the average arc and incandescent lighting systems.

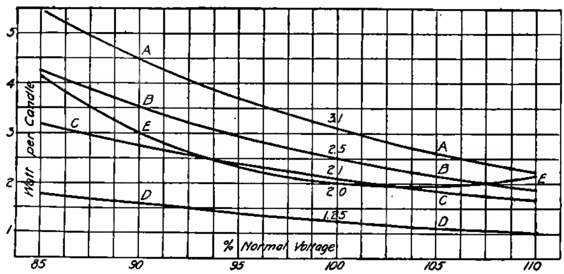


Fig. 54.

The **Westinghouse Nernst** is a new and improved form of the preceding lamp. This lamp shows a marked advance in efficiency and is made in four sizes of single-glower units, for both alternating and direct-current circuits. Moreover, this lamp operates directly on 110 volts, and is equipped for screw base renewals thus permitting any person to trim the lamp when burned out.

Fig. 54 shows the variation in consumption of the standard types of incandescent lamps with impressed voltage. Curve *A* refers to a 3.1 watt carbon filament lamp; *B*, a 2.5 watt graphitized filament lamp; *C*, a standard tantalum lamp; *D*, a standard tungsten lamp; *E*, a Nernst lamp.

CHAPTER VII.

ARC LAMPS.

Until the beginning of the present century the only method of arc lighting consisted of an arc between electrodes of carbon, and it has been only during the past few years that it has been understood that efficiency is not alone a question of temperature, but that by employing substances of a selective emissive power a light more economical, and at a temperature below that of the carbon crater, can be produced. The advent of the " flaming arc " lamp marks a new epoch in exterior illumination.

In lamps of the former class carbon is about the only satisfactory substance for the electrodes. It is highly refractory and the high temperature of the crater produced in the tip of the anode of the direct-current arc gives the highest efficiency available from incandescent bodies. About 85 per cent. of the total light from a direct current arc lamp comes from this crater and only about 10 per cent. from the negative electrode, while the flame in either the direct or alternating-current lamp is comparatively non-luminous. Carbon acts differently from any other substance as an electrode and makes the only practicable electrode capable of maintaining a steady alternating-current arc at low voltage.

The luminescence in lamps of the latter class is due almost entirely to the arc itself, little if any light coming from the electrodes. This luminous arc is produced in two ways: first, by a cathode composed of some of the oxides which feeds the arc stream with incandescent particles; and secondly, by the use of carbons impregnated with substances of high refractiveness as metals of the calcium group, which substance is fed into the arc stream directly from the cathode and passed into the stream as a vapor from the positive electrode.

As the electrodes of a lamp are separated after making the circuit, the current continues across the gap by means of a bridge of conducting vapors from the electrodes, established and maintained between the electrodes by the current. Heat is generated at the ends of the two electrodes and in the direct-current lamp, it is more pronounced at the positive electrode. The arc stream has the appearance of coming from a small space on the negative terminal, thence expanding somewhat and surrounding the anode with a diffused glow. The arc contains a small inner stream of an intensity dependent on the material of the electrodes, and it appears to be the real path of the current.

When the cathode is liquid as in the mercury vapor arc this negative spot passes around on the surface of the liquid in an erratic manner and with great rapidity, while if a solid metallic substance be allowed to float on this pool the negative point takes a position on one of its projections and becomes steady.

When a lamp is supplied by alternating current, nearly all arcs show a tendency, more or less marked, toward a uni-directional current within a certain range of voltage and operate poorly on alternating-current circuits. Between magnetite terminals a steady arc of $\frac{5}{8}$ of an inch in length can be maintained with a direct current of 4 amperes and 100 volts, but it is impossible to maintain an arc of even minute length, by means of alternating current, with less than 500 volts and then the arc is unsteady and noisy, and a direct-current ammeter connected in the circuit shows a partially rectified current.

In order to maintain illumination, energy must be supplied by the circuit. Most of this energy seems to be consumed at the arc terminals, as a potential drop, and varies but little, comparatively, for different lengths of arc.

Steinmetz has derived a theoretical volt-ampere equation for the electric arc, showing that the voltage consumed by the arc stream varies inversely as the square of the current and directly as the arc length, and that the total voltage between electrodes equals the voltage of the arc stream plus a constant quantity due to the counter electromotive force at the arc terminals. This constant depends on the material composing the electrodes. Steinmetz's equation for the electric arc is:

$$e = e_0 + \frac{a\,(1+c)}{\sqrt{i}}$$

For the carbon arc, $e_0 = 36$, $a = 130$, $c = 0.33$.
For the magnetite arc, $e_0 = 30$, $a = 123$, $c = 0.05$.

This formula and the above constants are for arcs in the open air and based on the assumption that the temperature of the arc stream is proportional to its superfacial area and also that the size of the arc stream is proportional to the current.

In the arc of constant cross-section, where the temperature and pressure vary with the current, as in the case of the vapor tubes, the form of the equation changes, and Steinmetz found the equation for the mercury arc to be:

$$e = 13 + \frac{1}{1.68\,d - 0.066\,i - \dfrac{1.3\,d^2}{i}}$$

with a non-volatile anode, and

$$e = 13 + \frac{1}{1.68\,d - 0.114\,i - \dfrac{1.3\,d^2}{i}}$$

with a mercury anode, where 1 is the length of the arc in inches, and d is the diameter of the arc in inches.

The **carbon arc lamp.** The light from this lamp, as previously stated, comes from the incandescent tips of the electrodes, and the higher the temperature of these electrodes the higher will be the luminous efficiency of the lamp. This fact accounts for the greater amount of light emitted from the direct current than from the alternating-current arc. The direct current causes a crater of high incandescence at the positive electrode, the temperature of which is somewhere near 3500 degrees centigrade, the volatilizing point of carbon. In the alternating arc neither electrode possesses a crater although both are at a much higher temperature than the negative carbon of the direct-current lamp.

In all types of carbon lamps the arc is drawn by means of an armature actuated by one or more solenoids connected in series with the carbons. In the multiple lamps the regulation of the arc is automatic—the longer the arc the less will be the current and the weaker the lifting power of the magnets, but in the series lamps the current is constant and the regulation of the potential across the arc is accomplished by means of "differential shunt" solenoids connected in parallel with the arc. As the arc lengthens, its voltage increases and this shunt takes a greater current; its magnetic field, being opposed to that of the series coil, weakens the lifting force on the armature, thus shortening the length of the arc.

These lamps are also provided with a cut-out, which operates when the shunt coils weaken the field set up by the series coils sufficiently. This cut-out shunts the current from the arc and series coils, thus allowing the arc to "feed." The cut-out has a low resistance in series with it so that when the carbons come together the current is again established in its normal path and the series coils again draw an arc. In case the carbons become consumed or inoperative the cut-out remains closed and thus the lamp is protected from destruction.

The regulation of the lamps is greatly benefited by the addition of a "dashpot," the function of which is to deaden the variations of the movable electrode and decrease the fluctuations of current and arc voltage, resulting in a steadier arc and a more constant illumination.

One disadvantage in the ordinary arc lamp, and especially so in the open lamp where the arc is short, is the interception of the light from the crater by the lower carbon. This greatly reduces the efficiency of the lamp and alters the distribution of light.

The open arc lamp proves most satisfactory with from 45 to 50 volts across the arc and a current of 9 or 10 amperes—the arc being steadier on a comparatively high current, and becoming more unstable as the voltage varies much either way from the values given above. The constancy of the light also depends on the quality of the carbons—the purer and softer the quality of the carbon, the steadier will be the arc and the lower the necessary voltage. The upper carbon is consumed about twice as fast as the lower and presents a blunt terminal, while the lower electrode is tapered toward the end due to the combustion of the heated portion in the oxygen of the air. The carbons used in the open arc lamps are usually solid and much harder and of poorer quality than are the carbons for the enclosed lamps.

The efficiency of the open arc lamp is much greater than that of the enclosed arc lamp, but the short life of the electrodes, due to the free access of air, makes the cost of maintenance, both for labor and material, much greater. As a result of this, the open arc lamps are being rapidly replaced by lamps having the arc enclosed by a close fitting glass globe. It can be seen from data on page 2 that this enclosing globe absorbs some of the light and lowers the efficiency of the lamp, but the life of the carbons is increased to about 150 hours for direct current and 100 hours for alternating-current lamps. This life depends on the rate at which oxygen is admitted, a certain amount of which is necessary for a maximum life per trimming. This is shown in the following table where carbons of 11.11 millimeters in diameter are used and burned at 8 amperes. The results show the effect of different size openings in the gas-cap on the consumption of the carbons.

Diam. of gas-cap opening in mm.	Clearance in mm.	Carbons	
		Positive mm. per hour	Negative mm. per hour
11.15	0.04	2.2	0.1
11.90	0.80	2.0	0.3
12.70	1.60	1.9	0.4
14.30	3.20	2.3	0.4
17.50	6.40	2.8	0.5
28.60	17.10	11.5	0.8

The consumption is least when the carbons are of greater length or when the arc is near the top of the globe and greatest when the arc is at the bottom of the globe.

In the enclosed arc lamp carbons of good quality are used and one or both are usually cored. This causes the flame to center or to travel steadily around the carbons, and prevents "chattering" in alternating arcs, which sometimes occurs to such an extent with solid carbons that the points become chrystalized and offer such high resistance that multiple lamps will not burn.

As the electrodes are decreased in size the loss in heat due to radiation becomes less and the illuminous efficiency is much greater, but the carbons are consumed at a much faster rate. Consequently the size of the carbon is based on these considerations and averages about one-half inch in diameter in the commercial types of lamps.

The enclosed lamp possesses the additional advantage that it operates satisfactorily on voltages of 75 or 80 volts across the arc and from 5 to 7.5 amperes. This greater voltage maintains a longer arc which lessens the amount of light intercepted by the lower carbon. Moreover, the intrinsic brilliancy is much less than in the open arc and the diffusing properties of the globe give a far better distribution of the light. The distribution curve of the light in a vertical plane from an open direct-current lamp is an elongated elipse with its major axis making an angle of about 45 degrees with the horizontal, while a lamp with the same wattage and an enclosing globe will give much more light in the horizontal and vertical directions but only about half as much in the direction of maximum illumination. Curves verifying this statement are shown in Fig. 55. Curve *A* shows the vertical distribution of light from a 7.5 ampere, enclosed alternating arc burning one-half-inch electra carbons, the upper solid and the lower cored, and equipped with opal inner and clear outer globes. Curve *B* refers to a 6.6-ampere enclosed direct-current lamp, having one-half-inch solid electra carbons and an opal inner and clear outer globe. Curve *C* shows the distribution of light from a 9.6-ampere open arc on direct current.

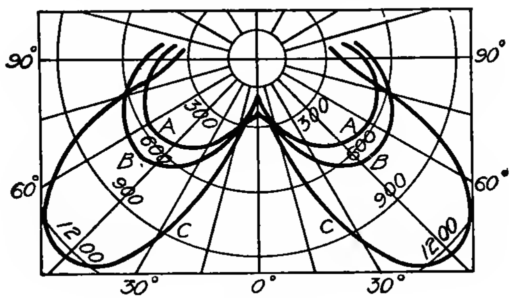


FIG. 55.

The carbons are $\frac{7}{16}$ inch National, copper plated and the lamp was supplied with a clear outer globe.

Carbon lamps are made for both alternating and direct-current circuits and for both the series and the multiple systems of distribution. The direct-current arc is the most efficient and gives about 25 per cent. more light for the same wattage than does the alternating-current arc. This is due to the much higher temperature of the positive carbon of the former.

The direct-current multiple lamp requires a steadying resistance in series with the arc to protect the lamp from short-circuit on starting and to steady the arc when burning. In the 110-volt lamp the voltage across the arc is about 80 which leaves 30 volts drop in the resistance. In the alternating current lamp this resistance is replaced by a reactance which answers the same purpose and consumes but little power. The result of these characteristics of the two types of lamps is that the direct-current lamp consumes about 30 per cent. more power in order to operate satisfactorily with the same arc consumption. Thus the low luminous efficiency of the alternating arc is offset by the greater electrical efficiency of the lamp as a whole.

This comparable equality no longer holds in the case of the series lamps, since practically no series resistance is necessary, and the ratio of the light from the arcs remains the same. The direct-current lamps, however, are usually energized by small units of comparatively low efficiency, especially on light loads. The alternating lamps, on the other hand, may be supplied by constant-current transformers which may receive energy from a distance, transmitted at high potential, or from large units generating power for other purposes as well. These considerations, together with the flexibility of the alternating current system makes the inequality of these two methods of arc lighting less than might at first appear.

The alternating-current arc is not very favorably accepted for interior lighting because of the humming peculiar to it. This may be due to the laminations in the reactance coil or armature or to the presence of air about the arc itself. The former defect can be overcome by good construction, the latter may be muffled by the addition of an outer globe as used on most interior lamps and lessened by burning the carbons at a high current density. Alternating lamps operate most satisfactorily on frequencies between 50 and 70 cycles per second. Above these values the lamp is liable to become noisy, while on lower frequencies a flicker will be perceptible.

The power-factor of an alternating arc lamp not only depends on the reactance in the windings of the lamp but on the reactance of the arc itself. The power-factor of the arc depends chiefly on the quality of the carbons; a very soft pure carbon will give a power-factor nearly unity, while a hard poor grade carbon may have a power-factor as low as 80 per cent. Tests showing these values for standard types of series and multiple lamps equipped with a standard make of carbons, were conducted by the writer and are given in part in the following table.

Type of Lamp	Cycles per sec.	Lamp			Arc	
		Volts	Amp.	Power-factor	Volts	Power-factor
A.C. multiple..	60	104	4.0	70	72	89
A.C. multiple..	60	104	6.0	70	72	94
A.C. multiple..	60	104	7.5	67	72	81
A.C. series.....	60	77	6.6	84	72	91
A.C. series.....	60	75	7.5	85	72	89
A.C. series.....	125	83	6.6	76	72	85
A.C. series.....	125	83	7.5	79	72	87
A.C. series.....	60	77	6.6	87	72	89
multi-frequency	125	81.5	6.6	81	72	85
A.C. series.....	60	77	7.5	85	72	88
multi-frequency	125	81.5	7.5	81	72	86

The relative efficiencies of the different types of lamps as given by Bell are:

Type of lamp	Watts per mean spherical c-p.	Remarks
Direct current series, open..........	1.0	Medium power arc
" " " shaded........	1.3	" " "
" " " enclosed.......	1.9	Approximate.
Alternating current series, open.....	1.7	"
" " " shaded...	2.2	"
Direct current multiple, enclosed....	2.4	No outer globe.
" " " "	2.9	Clear outer globe.
" " " "	3.3	Opal outer globe.
Alternating current multiple, enclosed	2.5	No outer globe.
" " " "	3.0	Clear outer globe.
" " " "	3.6	Opal outer globe.

In addition to the preceding we will devote a brief time to the study of the mechanical manipulation and the theoretical principles involved in some of the standard makes of lamps.

The simplest form of arc lamp is probably the direct-current multiple lamp a diagram of which is shown in Fig. 56. It will be seen that there is but one circuit through the lamp, the electricity enters at the positive terminal of the lamp, passes through the steadying resistance in the upper part of the lamp, thence through the

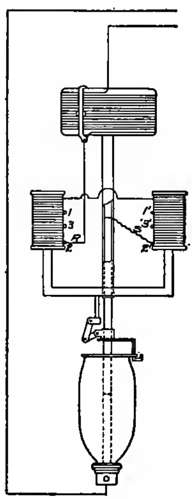


FIG. 56.

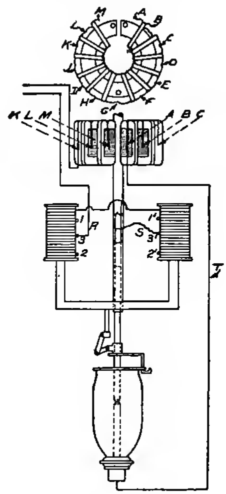


FIG. 57.

two solenoids which actuate an armature and draws the arc and then on through the carbons to the negative terminal of the lamp.

In Fig. 57 is shown the alternating-current multiple lamp. This differs from the preceding in that the resistance of the former is replaced by a reactance in the latter. It will be seen that the value of the reactance in series with the arc can be varied. By this means the lamp can be adjusted for different frequencies as well as for different current values on the same frequency. A second means of adjustment, for obtaining the desired values of current and potential drop across the arc, consists in changing the number of turns on the solenoids. All multiple lamps possess these two means of adjustment, namely, by changing the value of the resistance or reactance in series with the arc and by changing the number of turns on the lifting magnets.

One form of lamp for series direct-current circuits may be seen in Fig. 58. The construction of this lamp differs from that of the preceding lamps in that the steadying resistance or reactance is unnecessary, since the lamps are in series. However, while the multiple lamp regulates automatically, the series lamp requires a "differential shunt" winding in order to permit satisfactory arc regulation, and an automatic cut-out which allows the carbons to feed and protects the lamp from destruction if the carbons become consumed or inactive. The diagram shows three possible paths by which current may pass through the lamp, one through the series coils and the arc as in the multiple lamp, a second through the differential shunt, and the third through the starting resistance and the cut-out.

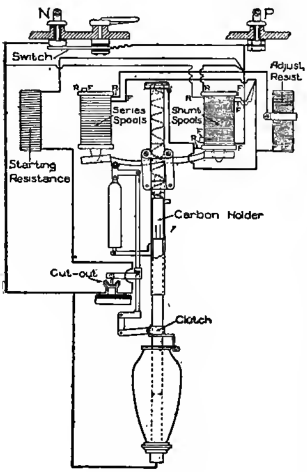


FIG. 58.

The working of this lamp, which is typical of series lamps in general, is as follows: Assume the lamp to be burning under normal conditions, the series coils having been previously adjusted, by means of the adjusting resistance in shunt with it, to give the desired arc voltage. Then the cut-out is open and the shunt coils are energized proportional to the arc voltage, and are not of sufficient strength to overcome the series solenoids. As the carbons are consumed, the voltage across the lamp increases consequently, the strength of the shunt solenoids soon becomes sufficient to lift their end of the armature which lowers the upper carbon. This continues until finally the cut-out closes, shunting the current through itself. The cut-out short-circuits the shunt coils and causes the series coils to become idle, the upper carbon is released and the two come together. The current then is established in the path of the least resistance which, due to the starting resistance, is through the carbons and the lamp again picks up. If

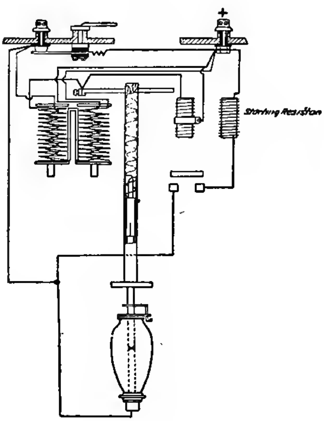


Fig. 59.

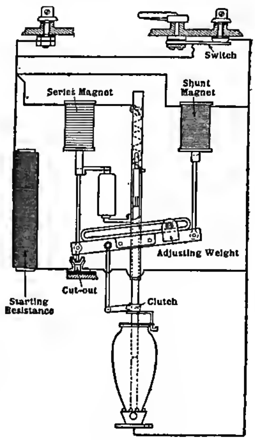


Fig. 60.

the carbons become inoperative the cut-out remains closed. The dash-pot is shown in the figure just above the cut-out.

Fig. 59 shows the diagram of another type of direct-current lamp. This is similar to the one last described except that the series and shunt solenoids are placed with one outside the other and have a common axis. The connections are so made that the field of the shunt coils acts against the field of the series coils.

A type of alternating-current series lamp is shown in Fig. 60. Its inherent peculiarities consist of a change in the design of the solenoid and the method of adjustment made necessary by the use of alternating currents. The armature of this class of lamps is always laminated and forms the core of the solenoids. Fig. 61 shows the method of connecting the shunt coils of this lamp for frequencies of 40, 50, 60, and 125 cycles. This involves the use of an auxiliary reactance made especially for this purpose.

In addition to the arc lamps already mentioned, there

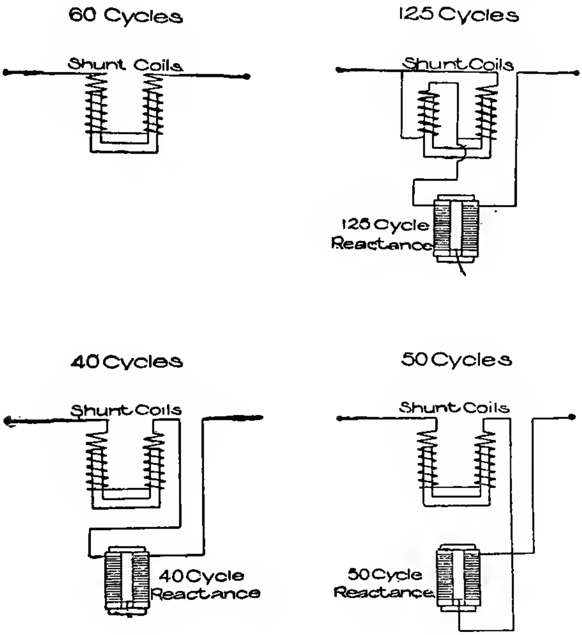


Fig. 61.

are lamps made for 220-volt, direct-current circuits, these have two sets of carbons placed side by side, connected in series, and maintaining two arcs. The connections for such a lamp are shown in Fig. 62. It will be seen that both arcs are governed by the same set of solenoids and that the circuit through the lamp is single and continuous and so arranged that the upper carbon of each arc is the positive. These lamps take about 2.75 and 3.25 amperes with a potential drop of 140 to 150 volts across the arcs, and are used chiefly where 110-volt circuits are not available. The arcs are unsteady and the regulation is less satisfactory than that of lamps employing larger currents.

The power-circuit lamp (Fig. 63) is a series-parallel

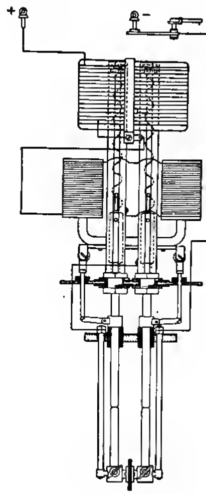


FIG. 62.

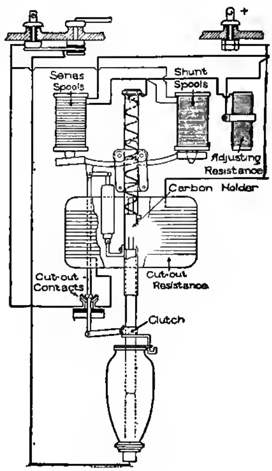


FIG. 63.

lamp made to operate, say 5 in series on a 500 volt power line. It is similar to the series lamp in construction and operation but has a resistance in series with the cut-out sufficient to take care of the arc voltage when the lamp cuts out and thus protect the other lamps on the circuit.

CHAPTER VIII.

FLAMING ARC LAMPS.

In this chapter we will consider those lamps which burn at atmospheric pressure and which owe their illuminosity to the incandescent particles in the vapor stream. In this type of lamp nearly all of the light comes from the arc stream, but little comes from the electrodes. This stream resembles somewhat, a candle flame and has its luminous and non-luminous zones. The non-luminous zones can be decreased in size and the luminous zones increased by increasing the amount, or changing the property, of the carriers in the arc stream. The metallic arc has such low resistance that the lamps will burn very steadily with a distance of 1.5 to 2.5 inches between electrodes. This greatly decreases the amount of light absorbed by the electrodes. Arc lamps employing impregnated carbons are commonly known as "flaming arcs." They will burn with either direct or alternating current but are more satisfactory on direct-current circuits. This type of lamp employs impregnated electrodes for both anode and cathode, since it has been found that if a substance is contained in the anode which boils at a temperature below that of the arc, that substance will evaporate out of the positive and in this way enter the arc stream, while the material of the cathode enters the arc stream directly, as heretofore described. One of the substances most extensively used in combination with carbon for making the electrodes is calcium, which on being fed into the arc flame gives a highly brilliant yellow light. This color is advantageous for exterior lighting, since the penetrating power in smoke or fog of a red or yellow light greatly exceeds that of a blue or violet light such as we obtain from the carbon arc lamp.

The chief objection to this class of lamps is the short life of the electrodes, one set of which will be consumed in from 8 to 17 hours. The more highly the electrodes are impregnated with the illuminous salts the shorter will be this life. At the same time the luminous efficiency of the lamp will be much higher as the per cent. of calcium is increased and to this fact may be attributed the reasons for the discrepancies in data on the luminous arc lamps.

There are four methods of making the flaming arc carbons: in one class the electrodes consist of cored carbons with their cores filled with the refractory substances; in another, the salts are contained in the core and in combination with the outer portion of the electrode as well; a third consists of a solid electrode with the metals in composition with the carbon; and a fourth consists of a solid electrode like the third but has a coating of pure carbon on the outside to decrease the oxidizing effect of the air. This variance in the construction of the electrodes constitutes the principal difference between some of the well known types of flame carbon lamps.

The color of the light from the flaming arc depends on the salts with which the carbons are impregnated. The yellow light from electrodes containing calcium is the most efficient. The red light obtained from the use of stroncium gives an efficiency 10 to 20 per cent. less than calcium. A white light which may be obtained by impregnating the carbons with titanium or barium is still less efficient—about 25 to 40 per cent. less than the calcium light. The following curves show the value and distribution of light from carbons placed in a vertical plane and impregnated with salts to give light of a white, red, and yellow hue. Curve *A*, Fig. 64 shows the distribution of the white light in a vertical plane; curve *B*, the red light; and curve *C* the yellow or calcium light.

The **Bremer lamp** is one of the oldest as well as most efficient of the flaming arc lamps and can be considered as typical of this class of illuminants. The mechanical design of this lamp was based upon the fact that an arc is much larger between carbons placed parallel or slightly inclined to one another than when placed in the same plane with their axes coinciding. Moreover, the lamp possesses the additional advantage that, since the carbons are supported from above, there is no lower carbon in the path of

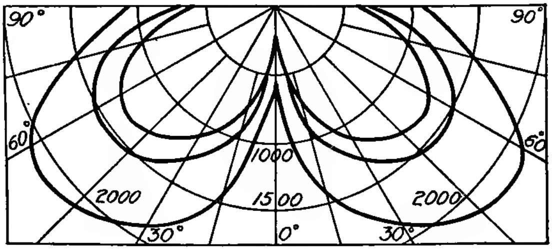


FIG. 64.

maximum illumination; and by the use of a magnetic field deflected downward, the arc can not only be prevented from climbing up the carbons but can be forced downward and outward giving a longer and larger arc and a better distribution of light.

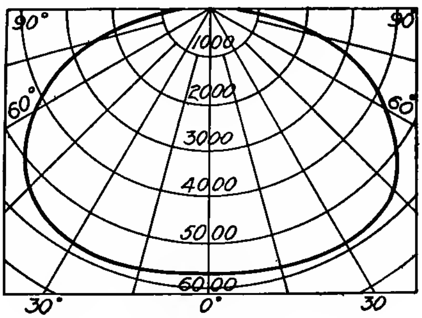


FIG. 65.

The distribution of light from one of the earlier lamps is shown in Fig. 65. This lamp was operating on direct current at 12.3 amperes and 44.4 volts without a globe. It was equipped with a conical shaped cap through which the electrodes projected. This lamp consumed 546 watts at the arc or a total of 677 watts if 55 volts are allowed for the lamp, and gave a maximum of 5630 candle-power and a mean hemispherical candle-power of 4800. This gives a specific consumption of 0.144 watts per mean hemispherical candle-power at the arc or 0.178 watts per candle for the specific consumption of the lamp. This lamp on alternating current showed a specific consumption of 0.312 watts per mean hemispherical candle-power.

The electrodes of the Bremer lamp are made from a paste consisting of carbon mixed with the salts of the calcium group to give the luminescence to the arc stream. The salts may constitute from 15 to 60 per cent. of the total compound but in practice it is usually limited to 25 or 30 per cent. A satisfactory electrode may contain from 10 to 60 per cent. of calcium flouride and 1 to 10 per cent. of the salts of potassium or sodium. The latter prevents a tendency of the arc to flicker. An intimate mixture of the finely divided elements is procured and the electrodes made by the squirting process similar to the method employed in the manufacture of carbons for the ordinary arc lamp.

When the electrode contains 20 to 30 per cent. of calcium flouride, a covering formed by coating the electrode with a solution of a mixture of borax, silicic acid, soluble glass and similar substances is desirable to insure mechanical strength. Moreover, before baking, the electrodes may be provided with small quantities of boron, common salt, potash, tartar, and similar silicates, which acting as a flux prevent the otherwise unavoidable scorifying of the electrode points.

The light from these electrodes is of a golden yellow color and contains very few blue or violet rays. The result of tests show an exceedingly high efficiency and a distribution of light well adapted for the lighting of large interiors where the lamps may be placed high and well out of the line of vision.

The **Westinghouse-Bremer lamp** is the form of the Bremer lamp made by the British Westinghouse Co., and differs little from it in construction. Since this lamp is typical of the converging carbon lamps a brief description of its construction and operation will not be out of place. Four solenoids are employed in this lamp—two striking or lighting coils, the shunt solenoid, and the arc controlling magnet. The striker coils are connected in series with the sub-resistance through a relay and across the lamp terminals. The plungers moving in the coils are coupled to a link and lever motion which releases or grips the carbons, operates the striker plate which swings up under the carbon tips to start the arc, and revolves the magazine to bring up a new pair of carbons. The shunt coil is in parallel with the arc and always in circuit, but its magnetic strength varies with the potential across the arc. It serves to attract an armature which acts as a switch to short-circuit the blow coil. This armature is released when the arc is normal, but is at once attracted when the arc fails or lengthens abnormally. The blow coil sets up a magnetic field repelling the arc from the ends of the electrodes and producing a long flame. It is normally in series with the arc but is short-circuited when the shunt relay is actuated and so releases an armature which, in falling, closes a switch, completing the circuit of the striker coils. The striker is a piece of metal which is passed forward across the points of the carbons completing the circuit and establishing an arc when withdrawn.

When the lamp is burning the striker coils are inactive; the shunt coil is energized but not sufficiently to attract its armature and the blow coil in series with the arc is also active holding up the relay in the striker coil circuit. As the arc lengthens the shunt coil becomes stronger until finally it raises the relay; the blow coil is short-circuited and in turn releases its armature and cuts in the striker coils. This at once exerts a pull on the mechanism which lowers the electrodes, swings round the striker plate and readjusts the arc. This operation of feeding the electrodes takes place so quickly that the light does not fail before the arc is reestablished in its normal position. A slight blink is caused by the passage of the striker under the electrode points. This description can be better understood by referring to Fig. 66.

The arc is surrounded by a hood which acts as a reflector when covered with the fine white particles given off by the arc. A number of these particles in an incandescent state are suspended in the atmosphere around the arc and tend to further increase the intensity of the illumination. The more recent lamps are equipped with a magazine which holds five pairs of electrodes and increases the burning life of a trimming to 40 hours.

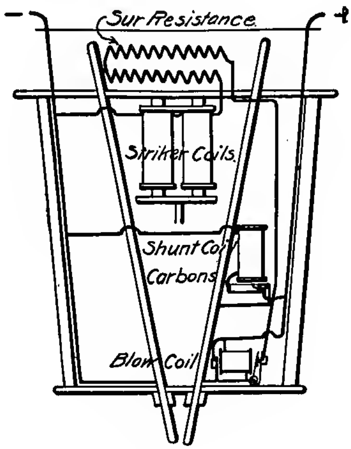


FIG. 66.

Tests on this lamp gave the following results:

	With globe	Without globe
Maximum candle-power....................	2400	5500
Mean hemispherical candle-power...........	1500	5000
Watts per maximum candle-power..........	0.18	0.081
Watts per mean hemispherical candle-power.	0.287	0.133

The flaming arc lamps used in this country are almost entirely of the inclined-electrode type. The distribution of light from an 8-ampere, 45-volt flaming arc is shown in Fig. 67. According to reports from the Electrical Testing Laboratories the lamp consumed 360 watts and gave a mean spherical candle-power of 1020; a mean hemispherical intensity of 1560; this gave a specific consumption of 0.353 watts per mean spherical candle-power and 0.265 watts per mean hemispherical candle-power. Curve *A* shows the distribution of light in the plane of the electrodes and curve *B* in a plane at 90 degrees to the plane of the electrodes.

The **Blondel flaming arc lamp** differs little in mechanical construction from the ordinary carbon lamp, its characteristic being the use of electrodes of special construction.

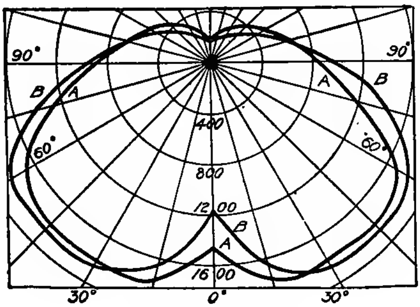


FIG. 67.

The electrode consists of a cylinder of carbon mixed with metals of the calcium group. This cylinder is encased by a covering of pure carbon to preserve the mineralized interior. This construction of the electrodes allows the use of low current densities without the danger of slagging. The carbons are placed vertically with their axes coinciding, which gives more light in the horizontal plane and less in a vertical direction. The efficiency of this class of lamp is high as will be seen from data on page 136.

The **Crompton-Blondel flame arc lamp** is a slightly modified form of the Blondel lamp. The electrodes are heavily mineralized and the efficiency slightly higher than the Blondel. The lamp is equipped with an "economizer" which is in reality a small reflector which becomes covered with a white sediment from the arc. The distribution of light from a 5-ampere arc may be seen from Fig. 68. This gives a mean hemispherical candle-power of 1850. The light is of a pale yellow or primrose color.

The **magazine flaming arc** is a German invention and is intended to do away with the great amount of care and attention required by the flaming arc lamps in general. The chief feature of this lamp is that it is so constructed that it can hold eight or nine pairs of electrodes, each 12 inches in length. These electrodes are of very small cross-section. The cores are larger than usual and contain the refractory elements necessary for a high efficiency. Because of the small cross-section, the electrodes are con-

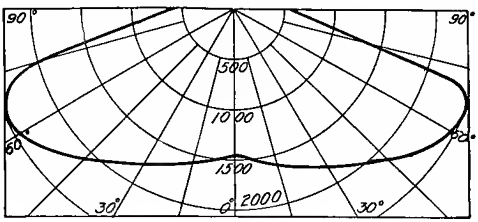


FIG. 68.

sumed rapidly while on the other hand poor quality of carbon can be used without impairing the steadiness of the light. The carbons are inclined at an angle of 22 degrees and are contained in the case. The arc burns at 35 volts. One set of electrodes will last about 5 hours.

The **magnetite arc lamp** owes its origin to the chemical research of Dr. Steinmetz in an endeavor to produce an arc lamp more efficient than the pre-existing types and at the same time having a life for its electrodes comparable with those of the enclosed arc lamp. The material of the cathode, as finally adopted, consisted of magnetite and titanium oxide. The magnetite particles make the arc stream a good conductor but they are not very luminous; consequently the titanium oxide is introduced to furnish the luminescence, playing the part taken by the calcium in the lamps just described.

It was found that the magnetite was consumed faster than was necessary to produce the same efficiency and a small amount of chromium was introduced, which has a higher melting point than magnetite although similar chemically, this restrained the molten magnetite and retarded the consumption of the electrode. There is no carbon in the composition of the electrode. Its life is from 150 to 175 hours. As in the carbon lamp the life can be increased at the expense of the efficiency or the efficiency can be increased by increasing the amount of titanium oxide which results in a shorter life. Magnetite cannot be used for alternating arc electrodes; consequently the magnetite lamp is direct-current apparatus.

The luminous intensity of the lamp is due to the incandescent particles of titanium supplied by the cathode and carried into the arc stream by the electric current. As a result of this phenomenon, the negative electrode is the only one consumed, if the anode, which is of copper, is of sufficient size to conduct the excessive heat and not reach the evaporization temperature. If the anode is of too great size, the material from the cathode will condense upon it; therefore, the approximate dimensions of the positive electrode must be determined from these two considerations. The spectrum of the arc shows the characteristics of the material of the cathode and is not affected by the constituents of the anode. In the case of the magnetite-titanium cathode, the light emitted is of intense brilliancy and whiteness. By reversing the direction of the current, the flame changes to a green copper arc of much lower intensity; and although the anode is always the hotter, the magnetite electrode is melted in the latter case. The magnetite electrode consists of a thin steel tube into which the oxides, carefully compounded, are tightly packed and the ends sealed.

The long arc of the magnetite lamp gives a better distribution of light than that obtained from the open arc carbon lamp, and requires only 4 amperes at from 65 to 75 volts to give the same amount of light as a 7.5 ampere 75 volt alternating arc such as are used extensively for street lighting.

In the General Electric lamp (Fig. 69) the magnetite electrode is placed below the arc, while in the Westinghouse lamp (Fig. 70) the negative electrode is above the arc. The two lamps are otherwise similar. When the lamp is first thrown in circuit the current energizes the starting

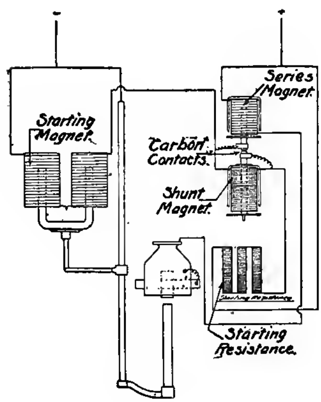


FIG. 69.

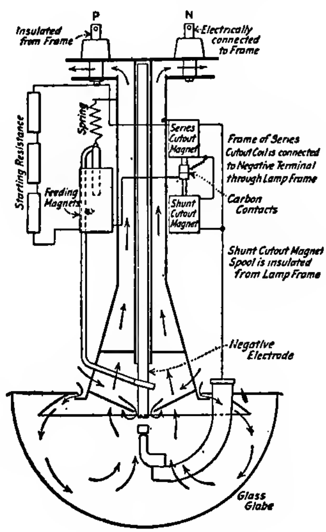


FIG. 70.

or feeding magnets, which raise or lower, the magnetite electrode until it makes contact with the copper electrode. Then the current is established through the electrodes and another coil called the series magnet which cuts in a shunt across the arc. This shunt is so designed that when the arc voltage has reached a certain value it throws in the feeding magnets, and the lamp feeds. In the Westinghouse lamp the upper electrode is supported in its proper position by means of a spring and the feeder coils act against this spring, lowering the electrode and striking the arc. It is claimed by the makers of this lamp that the distribution of light is made much better by placing the magnetite electrode above the arc since the luminous part of the flame is then in a position least shaded by the lower electrode, and the incandescent slag on the magnetite electrode reflects the light downward and outward.

The distribution of light from a 4-ampere magnetite arc consuming 304 watts is shown in Fig. 71. This lamp gave a mean spherical candle-power of 225, a mean hemispherical candle-power of 403, and a specific consumption of 0.75 watts per candle (hemispherical). A 7-ampere lamp gives a similar distribution of light and an intensity of 1500 candle-power 10 degrees below the horizontal.

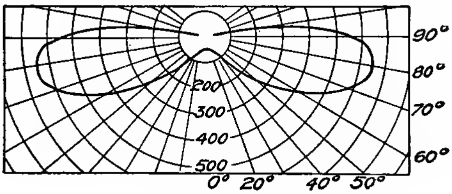


FIG. 71.

The life of the electrode is limited by its length—12 inches of active material gives a life of 175 hours.

The trouble experienced by the ventilating ducts becoming clogged by the residue of the flame was overcome by so designing the lamp that the heat from the arc and the wind outside the case would cause a draft through it. This overcomes the difficulty very successfully.

Seimens Bros. are making a magnetite lamp with the electrodes composed of 91.1 per cent. oxide of iron and the oxides of aluminum, calcium, magnesium, and silicon constituting the remainder. The specific consumption of this lamp is about 0.5 watts per mean hemispherical candle-power. Its light resembles that from the Bremer lamp in effect. The electrodes are inclined and both contained in the case of the lamp, and the light is well distributed over the lower hemisphere.

Because of the long life of the metallic arc electrodes, the small expense of maintenance, and the high luminous efficiency, the magnetite lamp gives promise of superseding the enclosed arc lamp for street lighting. They are designed to operate on series direct-current circuits and may receive energy from either a constant current arc dynamo or from alternating current circuits transformed into direct current by means of mercury arc-rectifiers. The current for the direct-current series systems of lighting by means of the mercury-arc rectifiers is first carried to a repulsion coil regulating transformer (constant-current transformer) and then through the rectifier to the lamps. The efficiency of the alternating current repulsion coil regulating transformer and the mercury-arc rectifier is about 90 per cent. and they are designed for about 2.5 per cent. line loss.

When used directly on alternating-current circuits the magnetite lamp should, theoretically, have two oxide electrodes and one copper electrode and operate on the principle of the Cooper Hewitt lamp for alternating currents; but instead titanium carbide is used to supply the arc carriers. This material does not show the tendency toward rectification that magnetite does and makes a very satisfactory electrode. The life, due to combustion of the electrode, is much shorter than that of the magnetite trimming, yet the titanium lamp can be classed as a long burning lamp.

The **mercury vapor arc lamp** is a combination of the ordinary enclosed arc lamp and the mercury vapor lamp. The enclosing globe is filled nearly to the top of the lower electrode with mercury. The lamp takes a current of 10 amperes at 50 volts. The upper carbon is the positive and the arc spreads out towards it on leaving the negative carbon. This arc increases in size as the mercury vaporizes. In the top of the globe is a condenser of sheet metal on which the carbon and mercury vapors are deposited, thus preventing blackening of the globe and returning the mercury which condenses. The arc travels around the carbons once in 10 or 20 minutes and is made up of three zones; the core of the arc is white, with a thin dark zone surrounding it, and surrounding all this is a thick yellowish candle-power at 30 degrees below the horizontal. The consumption of the carbons is slow, that of the positive being at the rate of $\frac{1}{4}$ mm. and that of the negative being at the rate of $\frac{1}{10}$ mm. per hour. The regulation is performed by hand and adjustment is required about once in 40 or 50 hours.

With larger electrodes and greater currents, much larger and longer arcs may be produced; and by using carbons

Type of Lamp	Mean spherical candle power.	Watts per Mean spherical candle-power	Hours life of electrodes
D.c. series, open	500	1.0	10
D.c. series, with shade	425	1.25	12
D.c. series, enclosed	250	1.9	150
A.c. series, open	300	1.7	10
A.c series, with shade	230	2.2	12
A.c. series, enclosed	175	2.8	100
D.c. multiple, enclosed no outer globe	275	2.4	150
D.c. multiple, enclosed clear outer globe	230	2.9	150
D.c. multiple, enclosed opal outer globe	200	3.3	105
A.c. multiple, enclosed no outer globe	200	2.5	100
A.c. multiple, enclosed clear outer globe	175	3.0	100
A.c. multiple, enclosed opal outer globe	150	3.6	100

mantle. No crater is formed in the positive carbon, and the color of the light depends upon the part which the mercury vapor takes in radiating the light and this in turn depends upon the height of the lower carbon above the mercury. When the volatilization of the mercury is rapid the containing globe becomes entirely incandescent.

A lamp of 2200 candle-power has a specific consumption of 0.31 watts per candle-power with a maximum impregnated with salts or by placing the salts on the mercury, the colors characteristic of the salts can be ob-

Type of direct-current lamp	Arc Volts	Amperes	Arc Watts	Mean hemi-spherical intensity	Watts per mean hemi-spherical c-p.	Milli-meters of elec-trode con-sumed per hour
Carbon electrodes....	40	9.0	360	700	0.514	14–16
Carbon electrodes enclosed arc..........	70	6.8	476	330	1.44	1– 2
Flame arc, vertical cored carbons.......	40	9.0	360	910	0.396	25–30
Intense flame arc inclined cored carbons.	45	9.0	405	2000	0.202	35–45
Magnetite lamp.......	91	3.5	320	400	0.80	1– 2
Bremer lamp, opal globe	48	9.0	432	970	0.116	30–40
Bremer lamp.........	48	9.0	432	2200	0.196	30–40
Bremer lamp.........	44.4	12.3	546	4800	0.144	35–45
Blondel lamp.........	48	3.0	144	1340	0.108	18–20
Blondel lamp.	48	5.1	245	2210	0.109	16–20
Crompton-Blondel lamp..............	48	5.0	240	1850	0.13	16–20
Blondel lamp.........	43	9.1	391	4800	0.081	16–20
Mercury arc lamp.....	50	10.0	500	1610	0.31	25– 1
Ferro-titanium arc.....	48	3.5	168	700	0.24	1– 2
Carbone luminous arc..	90	10.0	900	1070	0.84	18–20
Type of alternating-current lamp.						
Carbon electrodes.....	31	9.0	270	350	0.772	15–16
Cored carbons..	33	15.0	480	470	1.02	15–16
Flame arc, vertical electrodes.............	33	9.0	270	700	0.386	25–30
Flame arc, inclined electrodes.............	48	9.0	405	2000	0.202	35–45
Bremer lamp....... .	48	9.0	1110	1800	0.228	35–45
Blondel lamp.........	35	10.0	325	1890	0.172	15–20
Carbon enclosed arc...	72	6.6	525	315	1.67	1– 2

tained; or the mercury may be replaced by an amalgam to produce the desired effect.

Summary of arc lamps.—Data are given in the accompanying tables on some of the lamps in general use in this country and in Europe. These results, although obtained from the best authorities on lamps and probably represent the most favorable general conditions should be considered exemplary rather than final, since the constitution of the electrodes greatly influences the illuminating efficiency of the lamp. This is especially true in the case of the flaming arc lamps.

CHAPTER IX.

VAPOR LAMPS.

There are two distinct types of vapor lamps of commercial importance in this country, namely, the mercury vapor lamp and the Moore tube.

The **mercury vapor lamp** has been known since 1860, but the present commercial lamp was invented and developed by Mr. Peter Cooper Hewitt who discovered that economical results can only be obtained by a careful regulation of the temperature and density of the mercury vapor. The luminous part of the lamp consists of an exhausted glass tube containing a small amount of mercury, and when an electric current exists the mercury vaporizes and forms a stream of high conductivity. The mobility of the positive and negative ions in mercury vapor is said to be about 100 times greater than in air and the high conductivity of the vapor is supposed to be due to the much greater speed of the negative ions. The light is due to the incandescent particles in the vapor stream and it is assumed that the high temperature of these infinitesimal particles is caused by the collision of the positive and negative ions moving at such high speed. The temperature of the particles of matter in the tube after collision is exceedingly high but their size is so small that the resulting temperature of the lamp is comparatively low. The temperature of a Cooper Hewitt lamp taken by means of a thermo-couple was found to be 148 degrees centigrade at the anode, 164 degrees centigrade at the cathode, and 179 degrees at a point midway between the electrodes. The temperature of the cathode varied more than that of the anode, while the temperature of the vapor stream remained practically constant. The low temperature of the anode was due to its greater radiating surface.

Atmospheric temperatures have little effect on the efficiency of the commercial form of lamp since they are run at values on the flat parts of the curves and small changes in vapor pressure due to temperature changes are scarcely noticeable.

The characteristics of these lamps are interesting and peculiar. A specific consumption of 0.3 watts per maximum candle-power, considering the energy expended at the tube only, can be obtained with a proper current, size of tube, and vapor pressure. The efficiency varies with the vapor pressure, having a maximum value at a certain pressure.

The relation between the current, voltage and per cent. of maximum efficiency for a commercial type of lamp is given below:

Amperes	1.5	2.0	2.5	3.0	3.5	4.0	4.5
Volts	83	79	75	73	72	75	88
Per cent of maximum efficiency	64	80	92	98	100	90	68

It will be seen that the highest efficiency is concurrent with the lowest voltage, a fact both singular and fortunate, since for best regulation a low voltage across the tube is desirable. These data are given for a lamp having a one-inch tube. In order to obtain the same intrinsic brilliancy with other sizes of tubes the current must be changed in proportion to the cross-section. The voltage across the tube decreases as the size of the tube is increased, and the amount of light will be increased if the intrinsic intensity remains the same; consequently, a two-inch tube will give about 20 per cent. higher efficiency than a one inch tube, while the reverse occurs with tubes of smaller sizes.

The potential-drop across the tube when in operation, necessary to furnish the desired current, is comparatively insignificant considering the length of the tube. This loss in electromotive force cannot be considered as due to the ohmic resistance entirely, but is divided up between the vapor stream and the positive and negative electrodes. The voltage loss in the vapor is proportional to the length and inversely proportional to the diameter (not the cross-section) of the vapor stream, and amounts to about 1.33 volts per inch in length for a one-inch tube. It increases with the vapor pressure and is approximately independent of current densities, within certain limits.

At the positive electrode the drop is greater with a mercury than with a solid terminal, probably due to the greater vapor density near the surface of the mercury. This drop in voltage amounts to about five volts for positives of solid metallic substance and from five to eight volts for mercury positives. There is a drop of about four volts at the negative electrode and this is independent of the temperature and form of the electrode.

The electricity enters the mercury cathode at a small bright spot, which frits aimlessly over the surface and causes a depression in the mercury wherever it happens to be. If, however, a metallic body be placed in the mercury the stream will pass to its highest projection and remain there; or a magnetic field brought near the negative electrode will force the spot to the edge of the mercury where it will remain.

The mercury lamp with very little resistance in series with it is very unstable on a fluctuating voltage. To overcome this a special device, called the ballast, resembling that used in the Nernst lamp, is employed. This ballast is placed in series with the tube and having a high positive temperature coefficient of resistivity renders the operation of the lamp upon ordinary circuits very satisfactory.

To start the lamp the tube is tilted until the mercury makes electrical connection between the electrodes; this may be accomplished by hand or automatically by means of an electro-magnet. The lamp may also be started by causing a spark to pass through the tube by means of a high potential induction coil. This spark ruptures the medium and the current follows instantly. Still another method consists in placing an auxiliary positive near the negative for starting and then transfering to the other positive electrode.

After the lamp is started and while the temperature of the terminals are near that of the atmosphere, especially if the current is less than four amperes, there is a momentary tendency for the lamp to extinguish. It is evident that an impulse of voltage is desirable to meet this momentary increase in resistance; consequently, a reactance coil is used in series with the lamp.

An electromotive force of 25 volts will maintain an arc of several inches in length on direct current, while several thousand volts of alternating e.m.f. are necessary to establish the same arc. In fact the voltage must be high enough to rupture the medium between the electrodes, and when the arc is once established a current will exist only during the half cycle in which it started and a still greater voltage is necessary to establish the current in both directions. The theory of this phenomena is that the opposite alternation has to stop the arc stream of the preceding alternation in addition to establishing its own arc and overcoming the negative electrode starting resistance.

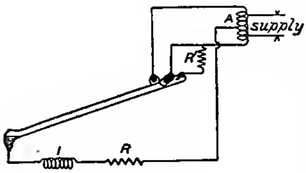


Fig. 72.

The alternating current lamp makes use of the principle of the mercury rectifier in addition to that of the mercury lamp and the current through the tube is uni-directional. It is started in a manner similar to the direct-current lamp and has the same specific consumption. It is intended to be used on frequencies between 40 and 125, and has a power-factor of from 80 to 85 per cent.

In order to operate the mercury lamp successfully on alternating-current circuits it becomes necessary to provide some means for preventing the cessation of the current at the zero points of the e.m.f. wave. This is accomplished by connecting the negative electrode to the middle point of a transformer winding and having two positive electrodes located at the same end of the tube and connected to the two ends of the winding, (Fig. 72). During one half cycle, current will exist from one end of the transformer winding through one positive electrode to the negative, while during the other alternation, current will exist through the other positive electrode. The choke-coil is in series with the negative electrode and since the current in the tube is uni-directional, the choke-coil becomes necessary to steady the current in the tube and to prevent it from falling to zero at the end of each half cycle. The alternating lamp also requires a ballast for best operation.

The Cooper Hewitt lamp, as commercially available

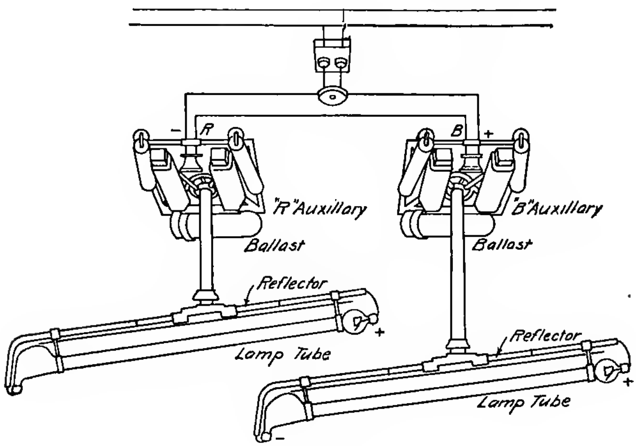


FIG. 73.

for general illumination operate on 3.5 and 4 amperes. The 3.5-ampere lamps have tubes about one inch in diameter and are made in two sizes; the type *K* lamp has a tube 45 inches long and gives about 700 candle-power; the type *H* lamp has a tube 21 inches in length and gives about 300 candle-power. The 4-ampere or type *P* lamp has a tube of the same length as the type *K* lamp but the tube is somewhat larger in cross-section and gives about 850 candle-power. The type *K* and type *P* lamps operate on 110 volts directly or two in series on 220 volts. The type *H* lamps operate two in series on 110 volts or four in series on 220 volts. The voltage across the tube is about 70 per cent. of that across the lamp for all the direct-current lamps. The type *C* or alternating current lamp operates on 110 volts, consumes 275 watts, and gives about 425 candle-power.

When the lamps are run in series, each lamp is shunted by a resistance, adjusted to consume the same power as the lamp. This resistance is cut out when the lamp is in operation; but if the lamp becomes inoperative the resistance takes its place thus preventing an interruption of the system. A diagram of the connections (Fig. 73) and the location of the parts of two lamps in series are shown in the accompanying figure.

In practice the engineers of the Cooper Hewitt company are lead to base their calculations for lighting with vapor lamps in accordance with the following data.

Service	Elevation	Type	Area per lamp. (sq. ft.)
Foundry..................	10 to 15 feet	H	800 to 1000
"	20 " 25 "	K	2000 " 2500
Machine Shop.............	10 " 15 "	H	375 " 600
Erecting work.............	20 " 30 "	K	1000 " 1500
Drafting..................	about 15 feet	H	150 " 250
"	" 20 "	K	250 " 500
General Office.............	10 to 15 feet	H	300 " 500
" "	20 " 25 "	K	500 " 1000
Rough work..............	10 " 15 "	H	1000 " 1200
" "	20 " 25 "	K	2500 " 3000

A prominent feature of the mercury arc is its bluish-green color. There are no red rays; therefore, any colors having red tints will be distorted, while those of a green or blue hue will be intensified. Black and white are about the only colors which appear in their normal state. This is the chief objectionable feature about the mercury vapor lamp and prohibits its use and adoption where color values are to be considered.

This light is strongly recommended for artificial illumination in drafting rooms and offices because of the almost harmless effect of its rays upon the eyes. Extended investigation having shown that the harmful physiological effects are due to the red and orange rays which predominate in the light from most artificial illuminants and which are wanting in the mercury vapor light.

Another noticeable feature of the light from the mercury arc is its penetrating power or better, the ability to distinguish details at a great distance. Without disputing the law of inverse squares it is evident that the sensitiveness of the eye, with decreasing intensities of light, decreases much faster for red or orange than for green or blue rays, or, what amounts to the same thing, the apparent physiological intensity of the bluish-green light decreases with distance much less than does the red light. This phenomenon has been discussed under Photometers.

The color of the light is so different from that of any of the accepted standards that any of the present methods of photometering are more or less unsatisfactory. There is little comparative data between this and other types of lamps and the results of different tests for specific consumption vary from 0.2 to 1.0 watts per candle-power; these discrepancies are, of course, due to the errors in photometry chiefly. The following report from the Central Electrical Laboratory, Paris, shows the unreliability of photometric data on lamps emitting light of entirely different color from that of the standard. A Bastian mercury lamp was photometered against a 32 candle-power incandescent lamp as a standard and was reported to give 14 candle-power at a distance of 1.86 meters form the screen. This result was not satisfactory and upon photometering the lamp at a distance of 21.5 meters from the screen the setting indicated 25 candle-power. In this case the error was attributed to the Purkinje phenomenon although the shape of the light source and the difference in the penetrating power of the light from the two lamps were suggested.

The following data from the Transactions of the National Electric Light Association by Prof. Clifford presents a study of the type *K* lamp on a 104-volt circuit.

	With Reflector	Without Reflector
Current	3.5	3.5
Average watts	364	364
Mean hemispherical candle-power	1200	575
Watts per mean hemispherical candle-power	0.303	0.630

In practice one type *K* lamp consuming 385 watts will give better results than a 5-ampere arc lamp consuming 550 watts, and will satisfactorily replace nine 32 candle-power incandescent lamps, giving twice the amount of light and consuming half as much energy, or twelve 16 candle-power lamps with three times the amount of light and about half the energy. One type *H* lamp requiring 195 watts will give better results than a 2.5-ampere arc lamp consuming 275 watts.

Many attempts have been made to replace mercury by some other metal but the difficulty consists in volatilizing and then restoring the negative electrode. Experiments have been performed at the Reichsanstalt to change the color of the light from the mercury vapor lamp and to rid it of that ghastly effect on certain colors. A lamp made from fused quartz was used and zinc in the form of zinc amalgam containing 30 parts by weight of mercury to 100 parts by weight of zinc, was substituted for the mercury. The zinc supplied the red rays and all colors appeared in their natural hue except yellow which appeared either too red or too green. This error was corrected by adding a small amount of metallic sodium and the light emitted was comparable with that of the Bremer arc lamp.

The addition of about 10 per cent. of bismuth was found advantageous since it prevented the cracking of the glass. The zinc amalgam solidifys at ordinary temperatures and without the bismuth would crack the glass upon expanding due to an increase in temperature. The lamps used in these experiments were not suitable for commercial purposes, and no data was given concerning the specific consumption of the lamp since it required further development to make it a practical success.

The **self starting Cooper Hewitt lamp** possesses the advantage of not having to be tilted to start it. This point recommends the lamp for service where it is impractical to start the lamp by hand and where automatic starters are not desirable. The current is started by applying a high potential across the tube terminals, thus breaking down the starting reluctance and allowing the current to be established through the tube at normal voltage. This high potential is created by interrupting the current through an induction coil in series with the lamp by means of a quick-break switch called the "shifter." The arrangement of the circuits can be seen from Fig. 74, where *A* is the shifter; *B*, the starting band; *C*, the inductance; *D*, the starting resistance; and *E*, the seiies resistance or ballast.

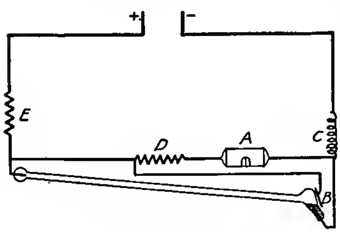


FIG. 74.

The lamp is thrown into circuit through the induction coil, the shifter, the starting resistance, and the ballast. The inductance coil actuates an armature which causes the shifter to open the starting circuit. Thus the inductance creates a potential between the tube terminals sufficient to break down the starting resistance of the tube. The fact that the tube starts instead of the current arcing across the ¼-inch gap in the sifter is brought about by an ingenious device applied to the tube which reduces the initial reluctance of the latter to a great extent and thus makes starting possible. This device is termed the starting band and consists of a metallic coating painted upon the outer side of the condensing chamber at the negative electrode of the lamp and extends above and a little below the level of the mercury inside of the chamber. It is connected to the positive terminal of the tube as shown in the diagram and thus experiences the full rise of potential against the negative electrode during the starting operation. The starting band and the mercury thus form the two sides of a condenser with the glass as a dielectric. When the high potential kick occurs minute sparks may be observed jumping from the surface of the mercury to the glass. These sparks appear to puncture the high resistance film at the surface of the negative electrode and the main current issues from one or several of these punctures.

The tubes are 50 inches long and made in the same shape as the tubes of the other lamps. The positive electrode is of iron. The auxiliary apparatus is housed in a compact case to which the tube holder is suspended. The lamp yields 800 candle-power at 3.5 amperes and 110 volts or 0.48 watts per candle-power.

The values of the watts consumed and the candle-power taken perpendicular to the axis of the tube as established by the makers and conceded by the best authorities are given below:

Type of lamp	A.c. or d.c. circuit	Length of tube	Candle-power	Watts per candle	Total watts
H	D.c.	21	300	0.64	192
C	A.c.	28	425	0.65	275
K	D.c.	45	700	0.55	385
Self starting	D.c.	50	800	0.48	385
P	D.c.	45	850	0.52	440

The **Bastian mercury vapor lamp** is a type of mercury lamp in commercial use in Europe. It operates on all voltages between 100 and 250, consumes 0.6 amperes and starts automatically when the switch is closed. The tube of the lamp is of hard Jena combustion glass $\frac{1}{8}$ inch in diameter and 10 inches long and made in the form of an S. The leading-in wires are platinum. The electrodes are of mercury and are normally connected by mercury. When the circuit is closed, the current through the lamp actuates an electromagnet which inclines the tube, causing the mercury to separate at a definite point and to pass to the positive end of the tube, thus drawing the arc and vaporizing the mercury. A lamp made for 220 volts will operate with variations in voltage from 160 to 300 volts. At the higher voltage the heat is so great that only Jena glass will resist it. The light between these limits varies approximately with the voltage. The spectrum shows the mercury lines with some violet. The yellow rays are very pronounced due to the high temperature at which the lamp operates. Experiments are being made with cadmium and sodium added to the mercury which renders the light quite normal. The Bastian lamp is chiefly used in combination with a carbon filament lamp and makes an excellent combination for general illuminating purposes. The life of the lamp is from 3000 to 5000 hours and some have burned for more than 10,000 hours and showed little effect of age. A renewal consists only in a new tube. The 0.6-ampere lamp are reported to give 90 candle-power.

The **high pressure mercury vapor lamp** is the name applied to a recent form of quartz lamp. If we will refer to the data for the Cooper Hewitt lamp we will see that there is a point of maximum efficiency which is at about 3.5 amperes in the one inch tube, and that above this point the efficiency decreases. The inventors of the new lamp conceived the idea that there would be a limit to this decrease in efficiency, which they found to be true and to occur at about one watt per candle-power. By increasing the amount of energy supplied to the lamp beyond this point, the specific consumption increased rapidly to about 0.2 watts per candle-power. This efficiency was, however, concurrent with a high temperature which only fused quartz would withstand.

In the ordinary mercury lamp the upper limit of the vapor pressure is about two millimeters. In the quartz lamp, when it operates at its best advantage, the pressure is about one atmosphere and it consumes about 0.25 watts per candle-power measured perpendicular to the axis of the tube. In this lamp the arc is much shorter than in the low pressure lamps—a 110-volt size having a length of 8 centimeters and a diameter of from 1 to 1½ centimeters. As a result of the small dimensions of the tube it can be mounted in a case and globe so as to resemble an arc lamp. The lamps are made to receive energy at 220 and 110 volts and are designed for 2.5 and 3.5 amperes. The results of Reichsanstalt tests show the following results:

Volts	Amperes	Horizontal candle-power	Mean spherical candle-power	Watts hor. c-p.	Watts mean spherical candle-power
174	4.2	2710	2360	0.269	0.309
197	4.2	3150	2740	0.262	0.302

By means of suitable reflectors a quite different hemispherical specific consumption could be obtained.

When the circuit is first closed the voltage across the tube falls to about 30 volts, consequently, a resistance of about 10 ohms in series with the tube becomes necessary. This low resistance at starting is advantageous since it is desirable to have as large a current as practicable in order to arrive as quickly as possible to the high temperature at which the lamp operates.

The lamp is quite expensive on account of the price of the fused quartz tube, but an old tube can be exchanged for a new one at comparatively small expense. The life of a tube is guaranteed for 1000 hours.

This lamp promises to be a successful competitor of the arc lamp as will be seen from the data. It has the further advantage of operating most efficiently on voltage higher than that practical for arc lighting. Furthermore, it will be seen that this lamp gives from 4 to 10 times the candle-power of the Cooper Hewitt lamp.

The color of the light and its properties have already been discussed. The ultra-violet rays are intercepted by using an enclosing globe of clear glass.

The **uviol lamp.** There has been much study of ultra-violet rays during the past fifteen years, and they have been found beneficial in the treatment of certain forms of disease and of service in exciting chemical activity. The mercury vapor light is rich in such rays but the ordinary glass used for the tubes of these lamps absorbs them. Following the necessity, Dr. Zschimmer has developed and improved a form of quartz glass called uviol which allows the spectrum to extend to 453 millionths of a millimeter, and makes a lamp very successful in transforming electrical energy into radiation of very short wave length.

In addition to the application of ultra-violet rays to medicine, they are being used extensively in photometric work. Under the influence of this light hydrogen and chlorine can be made to combine. Dyes can also be tested by the use of this lamp, since the bleaching action of the suns rays is due to the ultra-violet radiation. Experiments with the Cooper-Hewitt lamp, made with a uviol glass tube, indicate that the quality of dyes can be determined in a few days. Formerly dyes were tested in tropical countries where the sun's rays are more powerful and satisfactory results required several months. This lamp seems likely to replace the Finsen arc in the treatment of lupus, and skin diseases of various kinds since it is better, less expensive, and more easily applied.

Dr. Schott devised a so-called flourescence lamp, which is merely an ordinary uviol-mercury lamp having a great part of the long-wave radiation suppressed. This gives less light but causes flourescence in a great variety of substances which appear brighter than the lamp itself.

The **Moore lamp** represents the result of twelve years of persistent research and invention on the part of Mr. Moore. In theory it is similar to the Geissler tube and resembles the mercury vapor lamp in that it consists of a conducting vapor enclosed in a tube and owes its illuminosity to the incandescent particles of matter in the vapor stream.

The absolute temperature of these individual particles of matter within the tube after collision is supposed to be greater than any other temperature on earth. But the quantity of heat from each of these infinitesimal incandescent bodies is so small that in reality the external temperature of the tube is much lower than that of any other source of light.

The Moore tubes vary in length from 40 to 220 feet of continuous glass tubing and may be in any shape desired. The conducting gas is supplied to this tube—nitrogen, emitting a yellow light, gives the highest efficiency, while carbon dioxide gives a white light differing little from daylight. When the tube is fed with air alone the light is of a pale pink color.

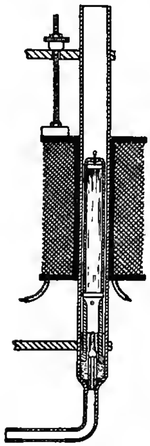


Fig. 75.

The terminals of the tube are brought to a terminal box and sealed upon carbon electrodes which serve the purpose of conducting the electricity to the gas. The terminal box contains a step-up transformer with its high potential side connected to the tube, and a regulating device to control the density of the vapor in the tube. The transformer may receive energy from any service mains at any commercial frequency. In order to insure a steady light an inductance of considerable value in the primary is necessary. This is accomplished either by employing a transformer of special design having a high coefficient of magnetic leakage or by introducing an adjustable inductance in series with the primary of a transformer of ordinary design. Recent improvements in the valve have made it practicable to adjust tubes to a power-factor of 85 per cent. The power-factor can be varied over quite a range by changing the vapor pressure in the tube which in turn is dependent upon the action of the valve.

The feeder mechanism is an essential part of the system. The passage of electricity through a conducting vapor will soon alter the condition of its vacuum. In the Moore tube the vacuum becomes higher and the resistance higher as the tube assumes incandescence. The result is that the light at first becomes unsteady, changing rapidly to violent spasmodic flickering, which soon ceases entirely and the tube gives no light. For satisfactory operation there must be some means for replenishing the gaseous conductor of the tube. This is accomplished by means of the feeder valve which operates automatically and supplies the tube with the necessary gas. This valve consists of a $\frac{7}{8}$-inch tube (see Fig. 75) supported vertically and its lower end contracted into a $\frac{3}{8}$-inch tube which extends to the main lighting tube. A $\frac{1}{4}$-inch carbon plug is sealed in the point of contraction by means of cement and surrounded by a small amount of mercury. The porosity of the carbon is not sufficient to allow the mercury to percolate

Pressure in millimeters of mercury	Amperes per volt per foot	Watts per candle-power
0.05	0.009	12.8
0.06	0.020	7.9
0.07	0.046	4.87
0.08	0.055	2.84
0.09	0.054	2.05
0.10	0.050	1.70
0.12	0.040	1.76
0.14	0.032	2.15
0.18	0.021	4.10
0.24	0.011	9.10

through it but will permit gas to pass easily due to the high vacuum of the tube at the lower end of the plug. Normally the mercury covers the carbon plug sealing the pores. Partly immersed in the mercury and concentric with and enclosed in the $\frac{7}{8}$-inch tube is another smaller and movable glass tube with its upper end filled with soft iron wire. This wire forms the core of the solenoid. As the current in the solenoid increases this latter tube is raised from the mercury which in turn falls away from the carbon plug and allows the passage of gas into the main tube. The variation of the current and specific consumption with different pressures can be seen from the above table.

If the lamp operates normally at 0.1 millimeter pressure the current per volt per foot will be 0.05 ampere; as the vacuum rises to 0.08 millimeter the current increases to 0.55 ampere per volt per foot. The strength and position of the solenoid is so adjusted that with this increase in current the inner tube will be raised from the mercury and a fresh supply of gas admitted to the main tube, thus decreasing the vacuum and the current. The degree of vacuum required in these tubes is about 0.10 millimeter. This vacuum can be maintained by this automatic valve within 0.01 of a millimeter or 0.00001 per cent. of an atmosphere either above or below the normal degree of vacuum, since a slight change in the vacuum causes a great change in the resistance. For example, a tube 220 feet long takes 24 amperes at its lowest working vacuum, but at the end of every minute the current has crept up to 25 amperes, when a new supply of gas is admitted and the current slowly falls again to 24 amperes.

The size of the transformer and the value of the secondary voltage depend on the length of the tube, as does also the primary current and the specific consumption. The action of tubes operated from 220-volt mains and giving 10.5 candle-power per foot can be studied from the following data.

Length of tube in feet	Watts required from the line	Primary amperes	Secondary volts	Watts per candle
25	800	6.0	2200	2.95
50	1400	10.0	4000	2.27
75	1850	13.0	5700	1.99
100	2250	15.7	7000	1.82
125	2600	17.2	8500	1.70
150	2900	20.5	9800	1.59
175	3200	22.5	11500	1.53
200	3500	24.5	12300	1.48
225	3750	26.25	13500	1.47

Tubes 40 to 70 feet in length require a 2.0 -kw. transformer.
" 80 " 125 " " " " " 2.75 " "
" 130 " 180 " " " " " 3.5 " "
" 190 " 220 " " " " " 4.5 " "

The feeder-valve solenoids are made in four sizes to correspond to these transformers. They are usually connected in series with the low-tension side of the circuit as shown in Fig. 76. The long tubes consist of 8.5 foot lengths of 1.75-inch glass tubing with walls $\frac{1}{16}$ inches thick, hermetically sealed. Various portable units of the Moore tube have been designed to operate directly from the line at line voltages. These give a specific consumption comparable with an arc lamp.

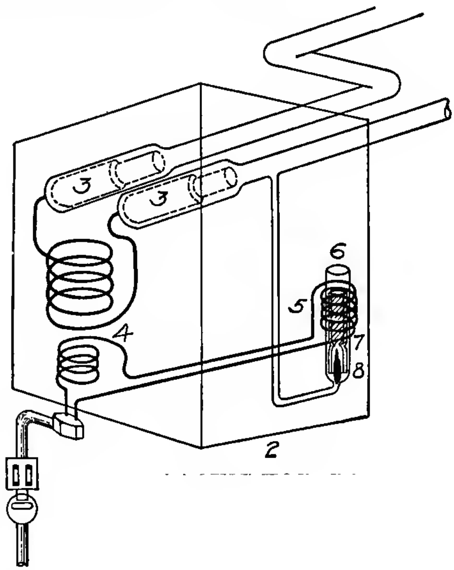


FIG. 76.

The results of tests given by Mr. Moore in one of his papers show a 140-foot tube to have $\frac{1}{5}$ of the specific consumption of incandescent lamps when lighting a theatre lobby; a 211-foot tube was found to have 2.9 times the illuminous efficiency of enclosed alternating current arc lamps when lighting a store basement. These results were for tubes supplied with nitrogen and giving a yellow light. With carbon dioxide and a white light the 211-foot tube gave an efficiency 1.5 times that of the arc lamps. Photometric tests showed a specific consumption of 2.84 watts per candle-power for a tube 40 feet in length and 1.59 watts per candle-power for one 220 feet long, when supplied with nitrogen.

The specific consumption of the tube and the intensity of the light remain constant throughout the life of the tube. The life of the tube appears to be indefinite—there being no reason for its destruction other than mechanical shocks.

The consumption varies but slightly with variations in voltage. The light intensity is directly proportional to the voltage and to the current in the tube. This intensity may be varied from almost nothing up to 25 candle-power per foot. The average tube operates at about 10.5 candle-power per foot in length.

It is claimed that the first cost of an installation of Moore tubes is less than an installation of incandescent lamps with the necessary wiring, fixtures and shades. The light from the Moore tube does not flicker and it is less susceptible to changes in voltage or current than any of the filament lamps.

In respect to color, steadiness, efficiency, diffusiveness, safety, low temperature and first cost, the Moore tube compares favorably with any of the other types of illuminants. The lamp is not affected by heat, cold, moisture or fumes. There is less danger of fires than from any other kind of an installation, and the high potential leads are enclosed in the terminal box thus insuring personal safety.

The color of the light from this tube can be varied over a wide range by changing the character of the gas in the tube. We have already noted that a tube fed with carbon dioxide gives a white light and that the nitrogen tube gives a golden-yellow light and if the tube is fed with pure air the result is an efficient pink light. The carbon dioxide is obtained from a piece of marble placed in a bottle with a little hydrochloric acid and the bottle connected with the valve tube—a small piece of marble will supply the tube for many months. The nitrogen for the yellow light is obtained by causing air to pass through an iron tube containing phosphorus. To regulate the amount of air coming in contact with the phosphorus, it has to first pass through a small mercury trap.

The Moore tube has a lower intrinsic brightness than any other source of light. When operating at 5.25, 10.5, and 31.5 candle-power per foot in length give 0.3, 0.58, and 1.75 candle-power per square inch of source respectively. These may be compared with the values for other sources given on page 3.

The Moore tube lamp was exhibited before a meeting of the American Institute of Electrical Engineers in its new assembly room in 1907. The room was normally lighted by concealed tubular incandescent lamps. An additional system of exposed incandescent lamps was installed parallel to the tube. This system consisted of new 3.5-watt, 117-volt lamps placed near the tube and 24 inches apart. The tube used was 176 feet long and formed a rectangle 62.5 by 25.5 feet; the diameter of the tube was 1.75 inches. The tube operated at 13 candle-power per foot. It had been used only 25 hours and had not attained its maximum efficiency which occurs when the lamp has been in service about 50 hours. The average results of the measurements of the illumination at nine different stations are given below:

	Moore tube system	Concealed system	Exposed system
Mean candle-foot illumination	3.24	1.75	2.18
Power factor in per cent	75	100	100
Area in square feet	1930	1930	1930
Volts	225	118	119
Amperes	24.5	86.4	42.4
Watts total	4150	10250	5050
Watts per square foot	2.15	5.31	2.62
Mean luminous efficiency-mean candle-foot illumination per watt consumed per square foot of floor area	1.50	0.35	0.83

CHAPTER X.

SHADES AND REFLECTORS.

It has already been shown by the distribution curves of light from the various sources of illumination that the natural distribution of light is often undesirable. Furthermore, the intrinsic brilliancy of the incandescent sources is almost always greater than is favorable for best effect or desirable for greatest comfort. Hence, the use of shades and reflectors. These may be classified into three general groups, viz:—shades, reflectors and diffusers, each group often merging more or less into the others, and combined with the others in various ways. A shade, as familiar to all, is an instrument for modifying the light by being placed between the source and the eye and may possess reflecting or diffusing qualities. A reflector is intended to redirect or modify the distribution of light and in accomplishing this end may act as a shade in certain directions. A diffuser is primarily intended to decrease the intrinsic brilliancy and prevent the glare accompanying many of our common illuminants, and may act as a shade or reflector.

There are a multitude of shades designed for purely decorative purposes and possessing no scientific or engineering value. Their illuminating effect is often detrimental and in many cases they are evil both in principle and application. Those only of practical significance will here receive attention.

One of the common types of shades and one extensively used in less expensive installations is the **Conical shade** made of tin and the interior surface painted with a bright, white enamel. This shade absorbs about 30 per cent. of the total light as ordinarily used. The distribution of light from a 16 c-p. lamp fitted with the common eight-inch shade is shown by curve *A* of Fig. 77.

The **fluted cone** is another well-known reflector. It is made of fluted porcelain, white on the inside and green on the exterior surface. Its effect on the distribution of light from a 16 c-p. lamp is shown by curve *B* of Fig. 77. This shade gives a higher efficiency than the enamel shade just mentioned, absorbing only about 12 per cent. of the light.

It will be seen that the former gives a more concentrated light while the fluted porcelain gives a more uniform downward illumination.

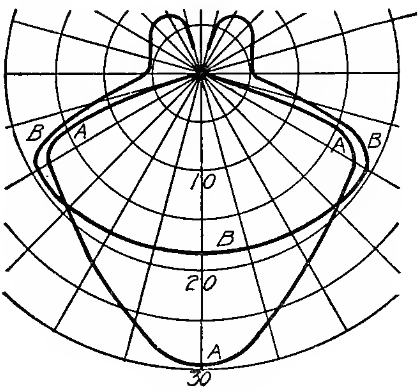


FIG. 77.

A very common type of reflector is the **flat fluted porcelain reflecting shade** which is used extensively with incandescent lamps and Welsbach mantles where an outward illumination is desired. The distribution of light from a 16 c-p. lamp equipped with a six-inch shade of this design may be seen from curve *A*, of Fig. 78.

The **McCreary shade** was designed to give a strong, concentrated light well diffused and accomplishes its purpose very successfully, as will be seen from curve *B*, Fig. 78, which represents the distribution from a 16 c-p. lamp in a 7-inch shade. This shade has a white porcelain, conical shaped upper interior while the lower part is enclosed by ground glass.

Fig. 79 shows the curves of a 4-c-p. **reflector lamp.** This lamp resembles the meridian lamp very closely in shape, except that the top and bottom are slightly flattened. The principal characteristic of the reflector lamp lies in the silver coating applied directly to the upper part of the bulb. Curve *A* shows the distribution of light for a plain bulb. Curve *B* shows the light with the top silvered and the

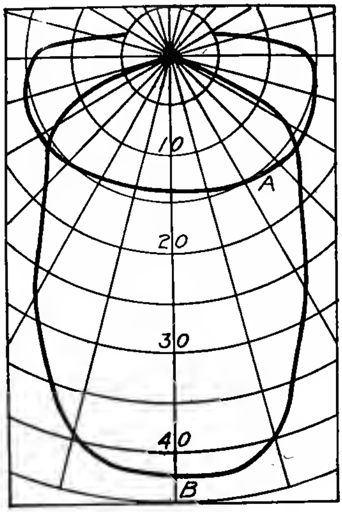


FIG. 78.

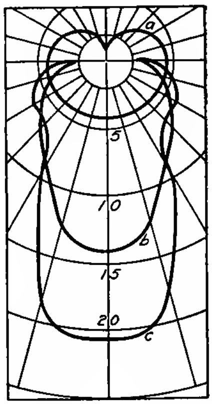


FIG. 79.

lower part frosted. Curve *C* shows the distribution with the top silvered and lower part clear glass. The 16-c-p. lamp of this class gives 17 c-p. maximum for *A*, 55 for *B*, and 82 for *C*. The 32 c-p. gives 38 for *A*, 120 for *B* and 185 for *C*.

This lamp is used with very pleasing effects for lighting show cases and display windows.

The **Linolite lamp** is the result of an endeavor to better the distribution of light from the carbon filament lamp. This lamp consists of a carbon filament placed lengthwise in a glass tube and straight except for a loop in the center which permits contraction and expansion of the filament or tube. The tube is hermetically sealed and electrical connections made at the ends. The Linolite lamp is equipped with a semicircular reflector 2.25 inches wide which is so constructed that the filament is uniformly located throughout its length in the focus of the reflector. Fig. 80 shows the vertical distribution of luminous intensity of Linolite as compared with the ordinary 16-c-p. bulb lamp, both having the same size and length of filament and consuming the same amount of electrical power.

Curve *A* refers to the bulb lamp and curve *B* to the tubular form of lamp. The Linolite system is so compact

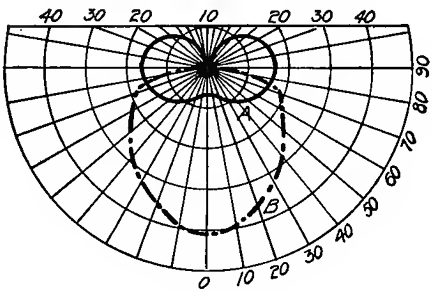


Fig. 80.

that it can be conveniently placed in show windows, show cases, etc. so that the fixtures will be invisible and the source of light screened from the eye of the observer.

The usual method of arc lighting with lamps of the enclosed type using other than clear glass globes is to combine them with opal globes and shades for the purpose of diffusion and reflection. The curves shown in Fig. 81 are for a 6.1-ampere 380-watt alternating-current arc with carbon electrodes. Curve *a* shows the distribution of light when an opal inner and opalescent outer globe are used: curve *b* for an opal inner and clear outer globe; and curve *c* for an opal inner globe and a shade of the shape shown in the figure.

A system of interior lighting with large candle-power units consists of arc lamps equipped as shown in Fig. 82, with concentric diffusers and lower shades. This method of distributing the light is very satisfactory for lighting stores, drafting rooms, and similar interiors furnishing a soft even illumination free from glare. When direct-current lamps are used, better results are obtained by reversing the arc, *i.e.*, making the lower electrode positive. By operating the lamp with a short arc, a light resembling daylight may be obtained.

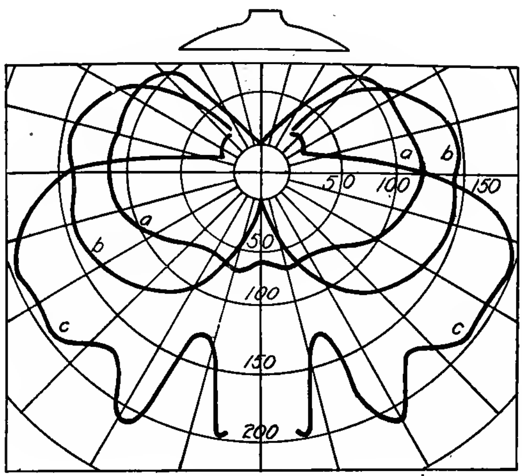


FIG. 81.

The shade is of heavy opal glass and reflects much of the downward light to the diffuser. The diffuser is made of sheet metal spinned into a concentric corrugated convex shape as can be seen from the diagram and covered with a white enameled paint. Thus the direct rays from the arc or the reflected light from the lower shade strike upon this diffuser and are spread outward and downward giving a well diffused and well distributed light.

The faults of the common reflectors are the high intrinsic brilliancy and glare accompanying their use. This calls for diffusion, and good diffusion without great loss in light is a troublesome problem.

The **Holophane globes** designed by M. M. Blondel and Psaroudaki are now in extensive use in this country and abroad. They represent an endeavor to obtain both

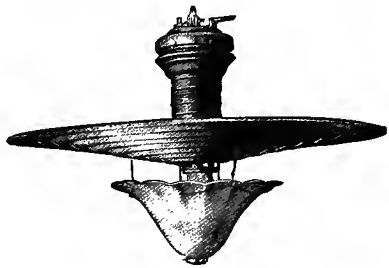


FIG. 82.

diffusion and redirection of the rays of light with minimum loss by absorption, and are the most efficient and satisfactory diffusing reflector on the market. The loss by absorption in globes for electric light is about 12 per cent. or a little higher than for clear glass.

This class of globes is made of pressed glass having a

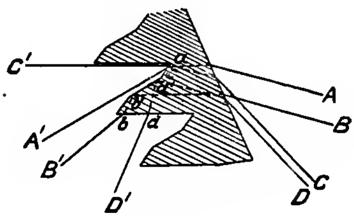


FIG. 83.

series of annular compound prisms on the external surface for changing the direction of the rays as may be seen from Fig. 83, and a fluting on the interior surface, for diffusing the light as shown in Fig. 84.

Referring to Fig. 83, it will be seen that those rays, the direction of which it is desired to change but little such as

A A' are merely bent by refraction only, while those requiring a greater distortion are reflected as well as refracted as shown by D D'. It will be seen that by properly shaping these reflecting and refracting surfaces any desired distribution of light can be obtained.

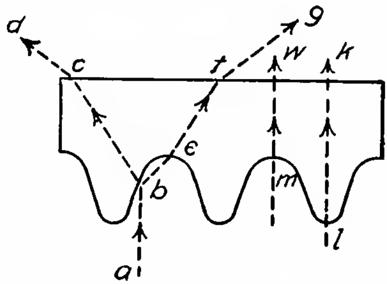


FIG. 84.

In order to obtain the diffusion required, the direct rays are broken up by the interior fluting as represented in Fig. 84. The rays making acute angles with these surfaces are split, part being only refracted while the other part will be reflected and refracted as shown by *a b d* and

FIG. 86.

a b g in Fig. 84. Those rays striking the surfaces normally are not affected. The external prisms are located horizontally around the globe while those on the inner side are vertical thus breaking up any bright streaks which might otherwise occur. These globes are made in many different shapes and for all types of illuminants, but can in general be divided into three classes, depending on the manner in which they distribute the light, and known as class *A* or concentrating globe; class *B* or distributing globe; and class *C* or sidewise illuminating globe. These globes are made for both upright and pendant positions and it is obvious that an upright globe will not give the desired results in a pendant position.

FIG. 87.

The general effect produced by these three classes of globes may be seen from Figs. 85, 86, and 87 respectively.

The Holophane reflectors are built on a different principle from the globes. They involve the principle that a right-angle prism is a total reflector of light. These reflectors are, in general, smooth on the inside, but with a series of vertical right-angle prisms on the outside. A small amount

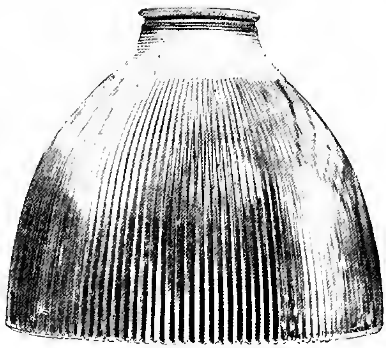


FIG. 88.

of light will pass through the top and bottom of each prism but the greater part of the light reaching the reflector will be thrown back with small loss from absorption. These reflectors like the globes may be divided into three general types classified according to the manner in which they distribute the light. For electric lamps, these are known as Types *B*, *C*, and *D*. The Type *B*, (Fig. 88) reflector is used for lighting interiors and gives a nearly uniform distribution of light over an area of 45 degrees each side of the vertical. The Type *C* reflector (Fig. 89)

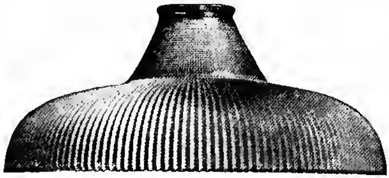
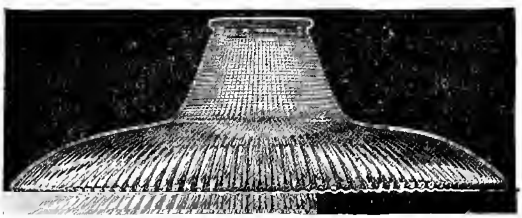


Fig. 89.

is recommended where a strong light is desired. The type *D* reflector (Fig. 90) is especially desirable where the ceiling is low and where the light is to be diffused over a comparatively large area. These are often known as the inverted bowl, the concentrating and the distributing reflectors, respectively.



[illegible] and 250 watts consumption, when supplied with type *B*, *C*, and *D*, reflectors give vertical distributions of light as shown in Figs. 91, 92 and 93, respectively.

The tantalum lamp when installed with *B*, *C*, and *D* type Holophane reflectors gives distributions of light similar to the preceding as shown in Figs. 94, 95 and 96, respectively. These curves are for 40 and 80-watt lamps of the ordinary type.

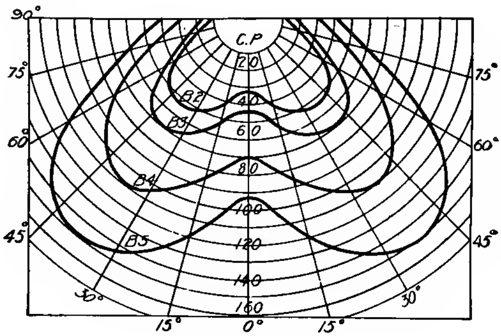


FIG. 91.

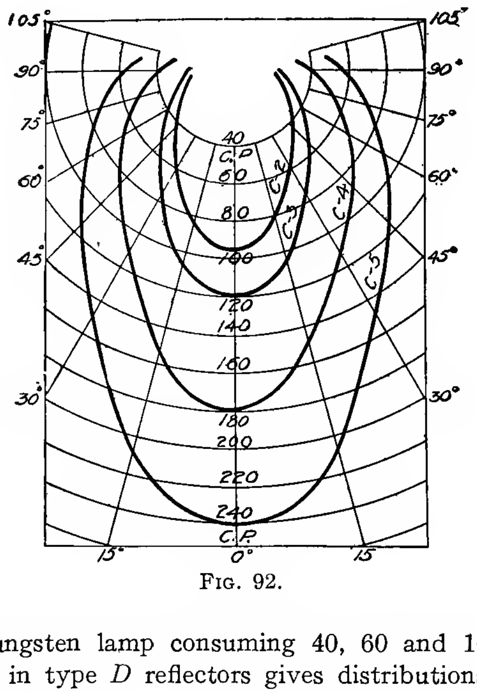


FIG. 92.

The tungsten lamp consuming 40, 60 and 100 watts, mounted in type *D* reflectors gives distributions of light shown in Fig. 97.

Reflectors of the concentrating and distributing models give results, when used with the tungsten lamp, similar to those obtained from the gem and tantalum lamps.

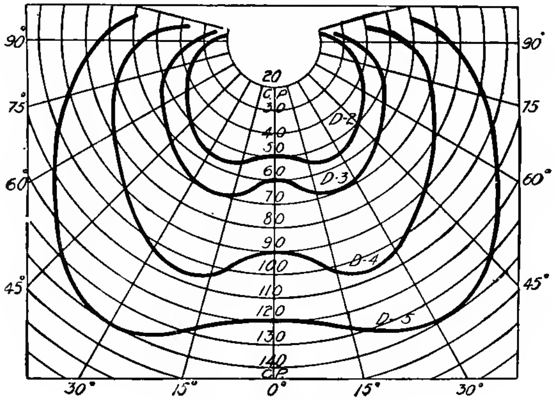


Fig. 93.

A recent development of the Holophane Company is a reflector for street lighting, to throw the light lengthwise of the street. That this is accomplished successfully may

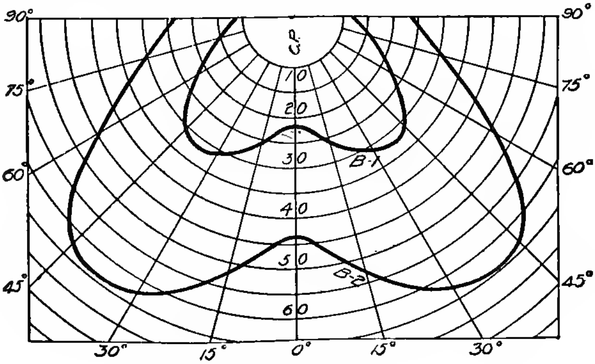


Fig. 94.

be determined from the curves for a 40-c-p. Gem lamp used in this reflector.

Fig. 98 shows the distribution of light around the lamp

10 degrees below the horizontal and Fig. 99, the distribution through a 65 degree vertical plane or a vertical plane through the maximum intensity points of Fig. 99. This

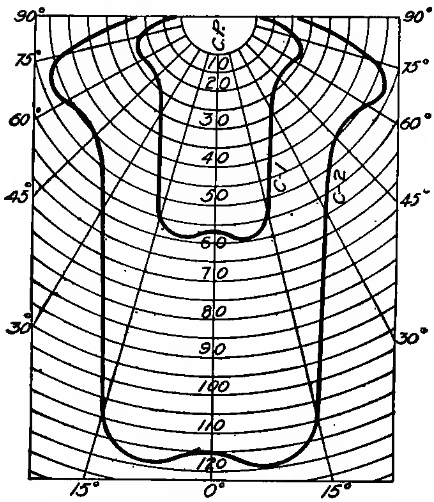


FIG. 95.

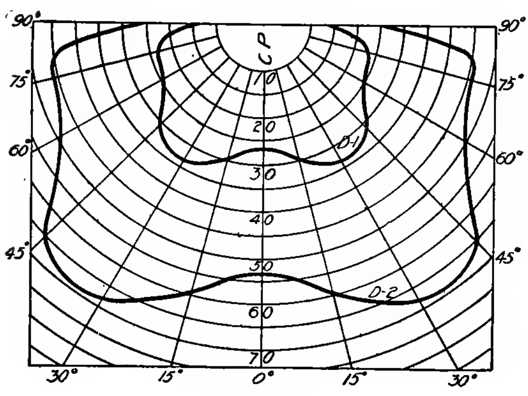


FIG. 96.

shade together with the tungsten lamp bids fair to revolutionize the present methods and mark the beginning of a new epoch in street lighting.

Two holophane globes of special design which seem worthy of mention are the ceiling bowl, a plan and distribution curves of which with a 50-c-p. lamp, are shown in

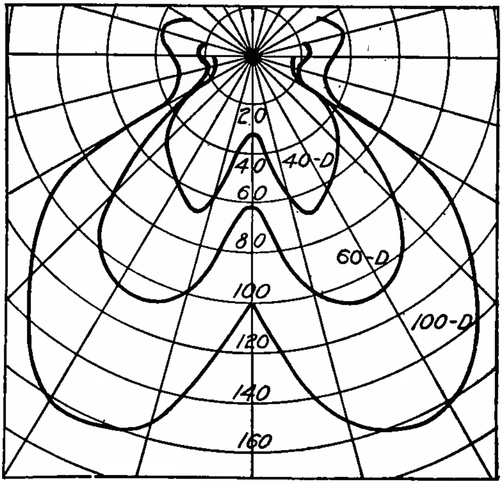


FIG. 97.

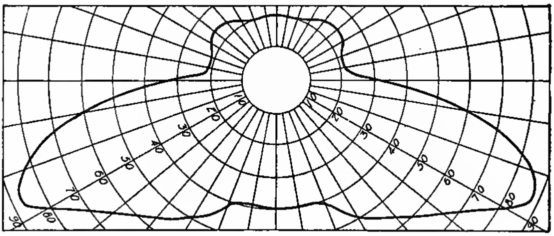


FIG. 98.

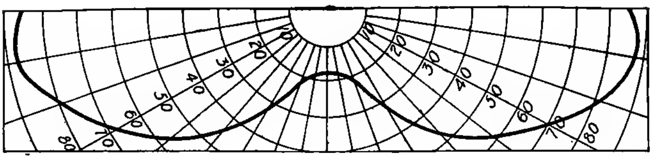


FIG. 99.

Fig. 100 and the sphere giving a distribution as shown in Fig. 101, when lighted by a 75-c-p. lamp.

In Fig. 100 curve *a* is for the bare 50-c-p. lamp, *b* for lamp and bowl, *c* for lamp and bowl and Holophane reflector.

In Fig. 101 curve *a* refers to the bare 75-c-p. lamp and *b*, the lamp enclosed in the sphere.

Holophane arcs are clusters of holophane shades intended for use with high efficiency incandescent lamps as a substitute for the ordinary arc lamp. The typical construction of such a cluster for six lamps is shown in Fig. 102 and the distribution for this cluster supplied with six-40-c-p., 100-watt lamps is shown by curve *A*, Fig. 103. In comparison with the distribution of light from this cluster may be seen by curve *B* that from a 6.25 ampere direct-current arc lamp having an opal inner and clear outer globe.

One of the chief requirements of the Holophane apparatus is cleanliness. The double grooved surfaces make excellent dirt catchers and the collection of dirt will greatly increase the absorption and lower the efficiency.

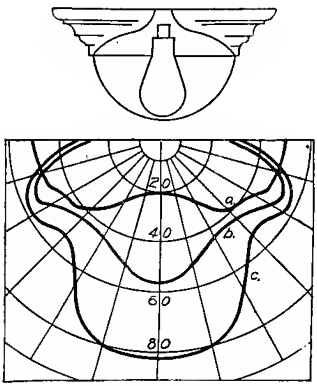


Fig. 100.

Moreover, they cannot be cleaned by ordinary dusting but thorough processes are necessary. However, if kept clean, the Holophane globes and shades will accomplish what is claimed of them, and in a manner surpassing any other type of reflector.

The effect produced by use of reflectors is likely to be misleading since from a casual glance at some of the curves showing the distribution of light from a lamp with and without reflectors one would get the impression that the total flux of light is greater when using reflectors than otherwise.

The highest efficiency is obtained from the bare, unshaded lamp, but the shade may reflect the rays in a direction where the light is desired at the expense of the regions

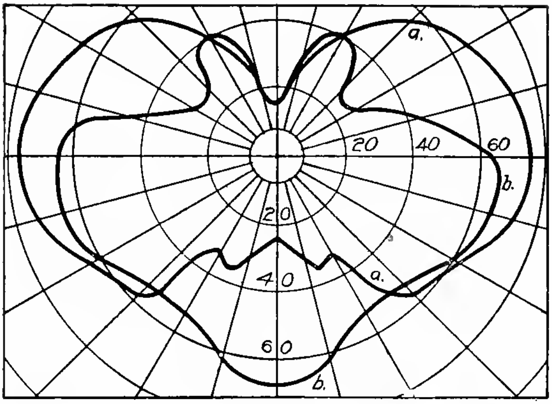
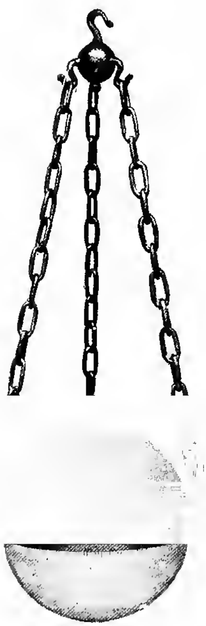


Fig. 101.



Fig, 101.

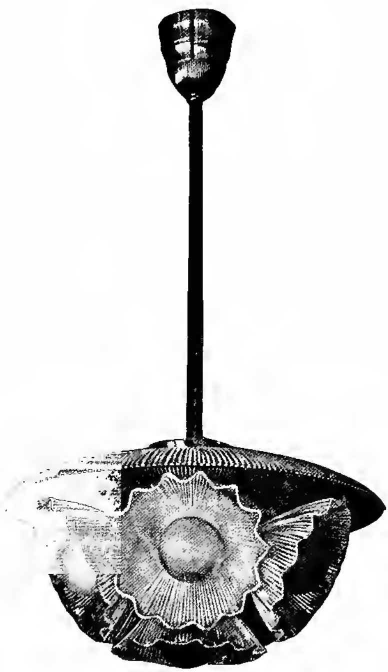


Fig. 102.

where light is not necessary. Suppose we use a reflector which will throw half of the light from a zone embracing the first 15 degrees below the horizontal, through a zone extending 15 degrees from the vertical, these zones have areas of the ratio of 7.66 to 1, we will have 3.83 times the intensity of light on the horizontal zone added to that in

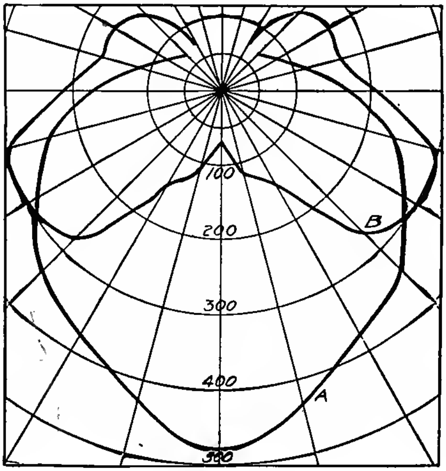


FIG. 103.

the downward direction. The curves of Fig. 92 and 93 have nearly equal efficiencies, but the curve of 92 appears to a decided advantage, while for general purposes, those of Fig. 93 will be the most satisfactory. To show this properly we must resort to the Rousseau diagram which is constructed as shown in Fig. 15.

CHAPTER XI.

ILLUMINATION CALCULATIONS.

The methods of determining the necessary value of the candle-power of a primary source of light in order to obtain the desired illumination intensity, and the calculation of the illumination when the distribution of light from the source is known will now be considered.

If we assume the source of light to be located at a point and designate the candle-power in a certain direction by I, then the intensity of light on a plane l feet away from the source and normal to that direction will be $\frac{I}{l^2}$ candle-feet. The intensity of light E_h on a horizontal plane making an angle α (Fig. 104) with this normal plane will be $E_h = \frac{I}{l^2} \cos. \alpha$. If now the height of the lamp, l_v above the horizontal plane be known, then $l = \frac{l_v}{\cos \alpha}$ or $l^2 = \frac{l^2_v}{\cos^2 \alpha}$ and by substitution we have:

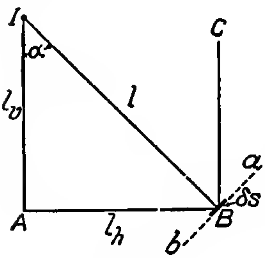


FIG. 104.

$$E_h = \frac{I \cos \alpha}{l^2} = \frac{I \cos^3 \alpha}{l^2_v}$$

This expression can be applied and a set of constants calculated whereby the intensity of illumination at a point on a horizontal plane or the intensity of a source for a desired illumination on a point on a horizontal plane can be easily determined.

If we let E_h equal the light in foot-candles on a horizontal plane; and the angle which the rays make with the perpendicular through the lamp; I, the candle-power in the direction α; l_v, the height of the lamp above the horizontal plane; and l_h the distance from a point under the lamp to the point illuminated, it will be seen that

$$E_h = \frac{\cos^3 \alpha}{l_v^2} I,$$

or by transposing

$$I = \frac{l_v^2}{\cos^3 \alpha} E_h,$$

which is the equation for the candle-power required to give an intensity E_h. We can now find and tabulate the values of $\frac{\cos^3 \alpha}{l_v^2}$ and $\frac{l_v^2}{\cos^3 \alpha}$ for different values of α and l_v as given in the following table. In these tables we will designate $\frac{\cos^3 \alpha}{l_v^2}$ by K.

As an example of the method of manipulating these tables we will find the illumination at a point on a plane 10 feet below a lamp whose distribution of light is known, as a six-glower Nernst lamp shown on page 103, the candle-power of which 60 degrees from the vertical is 296. The illumination at 17.32 feet from the vertical (see table) will be

$$296 \times 0.00125 = 0.37 \text{ foot-candles},$$

or the candle-power of the source in that direction necessary to give an illumination of 0.37 foot-candles at that point will be

$$0.37 \times 800 = 296 \text{ candle-power},$$

at an angle of 60 degrees to the vertical. These tables can be extended by multiples of 10—the various relations can be noted by comparing the values for heights of 2 feet and 20 feet.

α	0	10	20	30	40	50	60	70	80
l_v 1.									
K......	1.00	0.955	0.83	0.65	0.45	0.266	0.125	0.04	0.00524
l_h......	0.00	0.18	0.36	0.58	0.84	1.19	1.73	2.75	5.67
l/K....	1.0	1.05	1.21	1.54	2.22	3.77	8.00	25.0	191.
l_v 2.									
K......	0.25	0.239	0.207	0.162	0.112	0.0064	0.0313	0.010	0.00131
l_h......	0.00	0.35	0.73	1.15	1.68	2.38	3.46	5.50	11.34
l/K....	4.00	4.19	4.82	6.16	8.90	15.1	32.0	100.	764.
l_v 3									
K......	0.111	0.106	0.092	0.0722	0.050	0.0295	0.0139	0.0045	0.00058
l_h......	0.00	0.53	1.09	1.73	2.52	3.58	5.20	8.24	17.01
l/K....	9.00	9.42	10.8	13.9	20.0	33.9	72.0	225.	1720.
l_v 4.									
K......	0.0625	0.0597	0.0519	0.0406	0.0281	0.0166	0.00781	0.0025	0.000327
l_h......	0.00	0.71	1.46	2.31	3.36	4.77	6.93	10.99	22.69
l/K....	16.	16.8	19.3	24.6	35.6	60.2	128.	400.	3060.
l_v 5.									
K......	0.040	0.0382	0.0332	0.026	0.018	0.0106	0.005	0.0016	0.000209
l_h......	0.00	0.88	1.82	2.89	4.20	5.96	8.66	13.74	28.36
l/K....	25.	26.2	30.1	38.5	55.6	94.1	200.	625.	4770.
l_v 6.									
K......	0.0278	0.0265	0.0231	0.018	0.0125	0.00738	0.00317	0.00111	0.000145
l_h......	0.00	1.06	2.18	3.46	5.03	7.15	10.39	16.49	34.03
l/K....	36.0	37.7	43.4	55.4	80.1	136.	288.	900.	6880.
l_v 7.									
K......	0.0204	0.0195	0.0169	0.0133	0.00918	0.0054	0.00255	0.000817	0.000107
l_h......	0.00	1.23	2.55	4.04	5.87	8.34	12.12	19.23	39.70
l/K....	49.0	51.3	59.0	75.4	109.	185.	392.	1220.	9360.
l_v 8.									
K......	0.0156	0.0149	0.0130	0.0102	0.00702	0.00415	0.00195	0.000625	0.000082
l_h......	0.00	1.41	2.91	4.62	6.71	9.53	13.68	21.98	45.37
l/K....	64.0	67.0	77.1	98.5	142.0	241.0	512.0	1600.	12200.
l_v 9.									
K......	0.0123	0.0118	0.0102	0.00802	0.00555	0.00328	0.00154	0.000494	
l_h......	0.00	1.59	3.28	5.20	7.55	10.73	15.59	24.73	
l/K....	81.0	84.8	97.6	125.0	180.0	305.0	648.	2020.	

α	0	10	20	30	40	50	60	70
l_v 10.								
K......	0.0 0	0.00955	0.0083	0.0065	0.0045	0.00266	0.00125	0.0004
lh......	0.00	1.76	3.64	5.77	8.39	11.92	17.32	27.48
l/K....	100.	105.	121.	164.	222.	377.	800.	2500.
l_v 12.								
K......	0.00694	0.00663	0.00576	0.00451	0.00312	0.00184	0.000368	0.000278
lh......	0.00	2.12	4.37	6.93	10.07	14.30	20.79	32.97
l/K....	144.	151.	172.	222.	320.	542.	1150.	3600.
l_v 14.								
K......	0.0051	0.00487	0.00423	0.00331	0.00229	0.00136	0.000638	0.000204
lh......	0.00	2.47	5.10	8.03	11.75	16.69	24.25	38.47
l/K....	196.	205.	236.	302.	436.	738.	1570.	4900.
l_v 16.								
K......	0.00391	0.00373	0.00324	0.00254	0.00176	0.00104	0.000488	0.000156
lh......	0.00	2.82	5.82	9.24	13.43	19.07	27.71	43.96
l/K....	256.	268.	303.	394.	569.	964.	2050.	6400.
l_v 18.								
K......	0.00309	0.00295	0.00256	0.00201	0.00139	0.00082	0.000386	0.000124
lh......	0.00	3.17	6.55	10.39	15.10	21.45	31.18	49.46
l/K....	324.	339.	390.	.499.	721.	1220.	2590.	8100.
l_v 20.								
K......	0.00250	0.00239	0.00207	0.00162	0.00112	0.000664	0.000313	0.000100
lh......	0.00	3.53	7.28	11.55	16.78	23.84	36.64	54.95
l/K....	400.	419.	482.	616.	890.	1510.	3200.	10000.
l_v 22								
K......	0.00207	0.00197	0.00171	0.00134	0.000929	0.000549	0.000258	0.0000327
lh......	0.00	3.88	8.01	12.70	18.46	26.22	38.11	60.45
l/K....	484.	507.	583.	745.	1080.	1820.	3870.	12100.
l_v 24.								
K......	0.00174	0.00166	0.00144	0.00113	0.000781	0.000461	0.000217	0.0000695
lh......	0.00	4.23	8.74	13.86	20.14	28.60	41.57	65.94
l/K....	576.	603.	694.	887.	1280.	2170.	4610.	14400
l_v 26.								
K......	0.00148	0.00141	0.00123	0.000961	0.000665	0.000393	0.000185	0.000059
lh......	0.00	4.58	9.46	15.01	21.82	30.99	45.03	71.44
l/K....	676.	708.	815.	1040.	1500.	2550.	5410	16900.
l_v 28.								
K......	0.00128	0.00122	0.00106	0.000329	0.000573	0.000339	0.000159	0.000051
lh......	0.00	4.94	10.19	16.17	23.49	33.37	43.50	76.93
l/K....	784.	821.	945.	1210.	1740.	2950.	6270.	19600.

The following tables will be found more convenient and more applicable to interior lighting where the section under consideration will often receive light from more than one source. The calculations of illumination intensity and of the candle-power of the illuminating source are performed, as from the preceding tables.

l_h	0		2			4			6		
l_v	α^0	K	α^0	α'	K	α^0	α'	K	α^0	α'	K
2	0	.250	45		.0883	63	–25	.02240	71	35	.00790
4	0	.0625	26	35	.0447	45	00	.02206	56	20	.01064
6	0	.02775	18	25	.02365	33	40	.01600	45	00	.00980
8	0	.01563	14	00	.01428	26	35	.01119	36	50	.008015
10	0	.0100	11	20	.009417	21	50	.007997	31	00	.0063
12	0	.006945	9	30	.00665	18	25	.00592	26	35	.00496
14	0	.005105	8	10	.004905	16	00	.00453	23	10	.00397
16	0	.00391	7	10	.003818	14	00	.003567	20	35	.003202
18	0	.00309	6	20	.003030	12	30	.002875	18	25	.002648
20	0	.00250	5	45	.00246	11	20	.002355	16	40	.002197
22	0	.002065	5	10	.002047	10	20	.001963	15	15	.001852
24	0	.001736	4	45	.001715	9	30	.001662	14	00	.001582
26	0	.00148	4	25	.001465	8	45	.001428	13	00	.001369
28	0	.001276	4	5	.001265	8	10	.001225	12	5	.00119
30	0	.001111	3	50	.001105	7	35	.00108	11	20	.001045

l_h	8			10			12			14		
l_v	α^0	α'	K	α^0	α'	K	α^0	α'	K	α^0	α'	K
2	76	00	.00355	78	40	.001907	80	35	.001109	81	50	.000722
4	63	25	.00560	68	10	.00322	71	35	.001975	74	5	.001436
6	53	5	.00602	59	00	.003802	63	25	.002485	66	50	.001689
8	45	00	.00552	51	20	.003815	56	20	.002665	60	15	.001913
10	38	40	.004757	45	00	.00353	50	10	.002623	54	30	.00196
12	33	40	.0040	39	50	.00312	45	00	.00245	49	25	.0019
14	29	45	.003335	35	35	.002745	40	40	.00222	45	00	.001801
16	26	35	.002795	32	00	.002383	36	50	.002001	41	10	.001665
18	24	00	.002353	29	5	.00206	33	40	.001781	37	55	.001517
20	21	50	.00200	26	35	.001786	31	00	.001575	35	00	.001375
22	20	00	.001711	24	30	.001553	28	35	.001398	32	36	.00124
24	18	25	.00148	22	35	.001365	26	35	.00124	30	15	.001118
26	17	5	.00129	21	5	.00120	24	45	.001108	28	20	.001008
28	16	00	.001132	19	40	.001062	23	10	.000991	26	35	.000911
30	14	55	.001002	18	25	.000947	21	50	.000889	25	00	.000826

l_h	16			18			20		
l_v	α^0	α'	K	α^0	α'	K	α^0	α'	K
2	82	55	.000473	83	40	.000341	84	15	.000242
4	76	00	.0008875	77	30	.000631	78	40	.000476
6	69	25	.001207	71	35	.000876	73	20	.000654
8	63	25	.001402	66	00	.00105	68	10	.000805
10	58	00	.00149	60	55	.001149	63	25	.000897
12	53	5	.001506	56	20	.001181	59	00	.00095
14	48	50	.001455	52	10	.001178	55	00	.000965
16	45	00	.00138	48	25	.001142	51	20	.000954
18	41	40	.001288	45	00	.00109	48	00	.000927
20	38	40	.001189	42	00	.001025	45	00	.000883
22	36	5	.001088	39	20	.000955	42	20	.000835
24	33	40	.00100	35	50	.00089	39	50	.000785
26	31	35	.000915	34	45	.000821	37	35	.000736
28	29	45	.000834	32	45	.000758	35	35	.000686
30	28	5	.000765	31	00	.00070	33	40	.00064

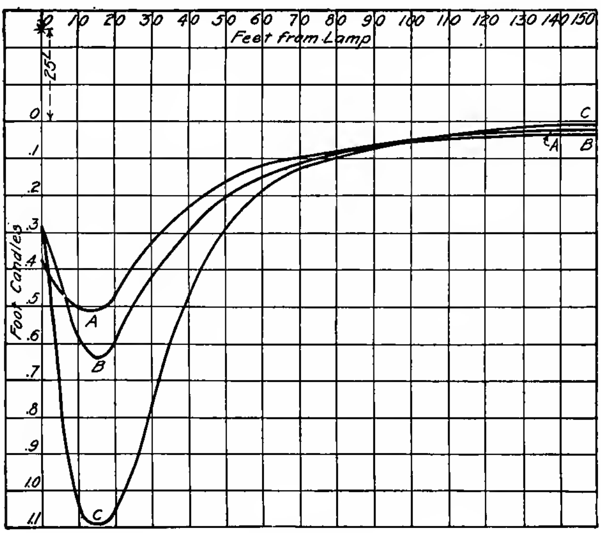


FIG. 105.

By the use of these tables and knowing the distribution of light from sources of illumination, it becomes a simple problem to calculate and plot the illumination curves for surfaces lighted by those illuminants. These results may be shown in several ways. One of the methods in practice is to plot the curves as shown in Fig. 105. These curves show the horizontal illumination from: *A*, a 7.5-ampere alternating current enclosed arc lamp having an opal inner and clear outer globe; *B*, a 6.6-ampere direct-current en-

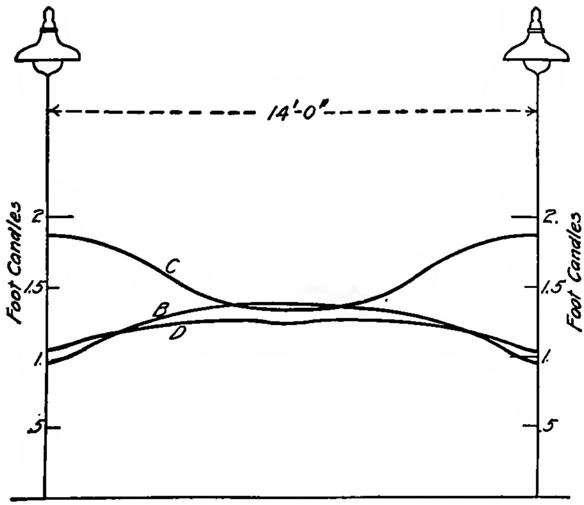
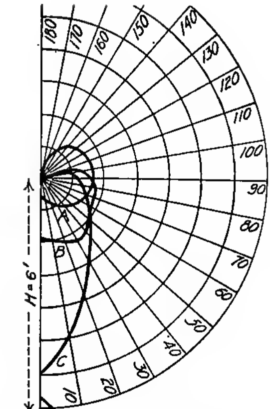


FIG. 106.

closed arc lamp having an opal inner and a clear outer globe; *C* a 9.6-ampere open arc lamp on direct current. The distribution curves for these lamps showing the light in a vertical plane may be seen from Fig. 55, page 115. The open arc shows up to advantage in Fig. 55 and also at first glance at Fig. 105 but closer examination will disclose the fact that a more uniform illumination is obtained from the enclosed alternating-current arc. This method of studying the illuminating values of lamps probably possesses a fairer and more practical means of comparing lamps



DATA—CURVE C.

D	θ	$\cos^3 \theta$	$C\ P$	I_h
0	0	1.000	58	1.62
1	9	.963	52	1.39
2	18.2	.860	39	.932
3	26.5	.716	32	.636
4	33.5	.580	27	.435
5	39.5	.459	25	.318
6	45.	.362	22	.22
7	49.5	.273	21	.159
8	53.5	.218	20	.121
9	56.0	.175	19	.0925
10	59.0	.137	18	.0685
12	63.3	.0389	17	.042
14	66.5	.0633	16.5	.029
16	69.3	.0460	16	.0204
18	71.3	.0320	15	.0133
20	73.2	.0248	14	.00965

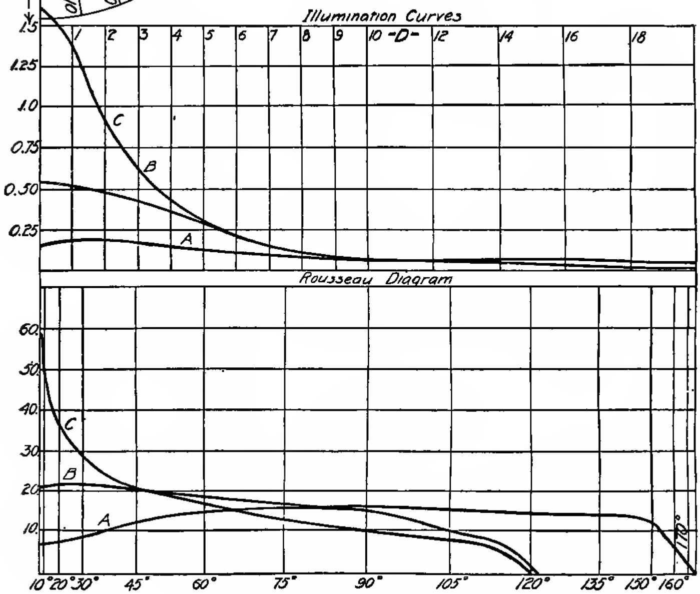


FIG. 107, FIG. 108, FIG. 109.

Lamp, 16 c.-p. Carbon Filament.

Curve A, Bare Lamp. Curve B, Type D Holophane Reflector.

Curve C, Type C Holophone Reflector.

than the vertical distribution curves or the Rousseau diagram.

This method of representing the performance of different lamps can be extended to calculations of illumination from more than one source. An example of this method of showing illumination intensities is illustrated by Fig. 106, which shows the results obtained from two 250-watt Gem

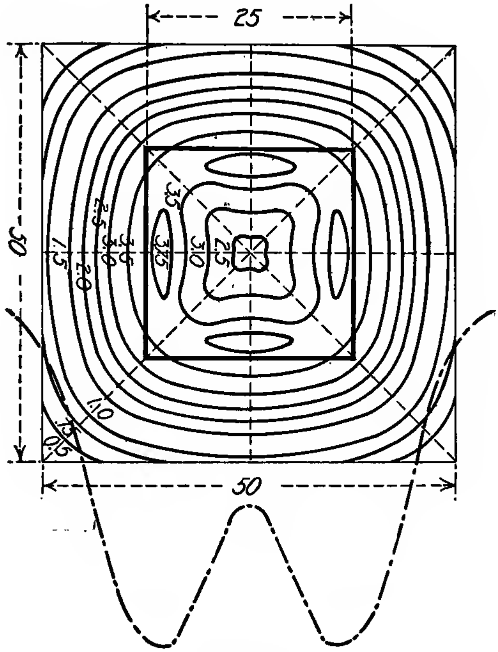


FIG. 110.

units spaced 14 feet apart, 12 feet above the floor, and equipped with type *B*, (bowl) *C*, (concentrating) and *D*, (distributing) holophane reflectors.

A convenient form of sheet for showing the characteristics of a lamp or lamps may be seen on the following page. Fig. 107 shows the distribution of light from a bare 16-c-p. lamp and the same lamp having type *C* and *D* Holophane reflectors. In Fig. 108 are shown the illumination curves for the same lamps when placed six feet above the floor. Fig. 109 shows the Rousseau diagram from which may be obtained the mean spherical or mean hemispherical candle-power.

A very satisfactory method of showing the illumination intensities over certain areas is to lay off the illuminated surface to some convenient scale and calculate and plot equi-luminous lines. Such a diagram may be constructed as shown by Fig. 110, which illustrates the distribution of illumination intensity from four sources of rather strong downward intensity, placed above the areas receiving the highest illumination. The vertical distribution of light through the center of the surface is shown by the broken line at the side of the diagram.

The calculations thus far have had to do with determining the illumination from light sources on a horizontal plane. It is often desirable to determine and moreover important to know how to calculate the polar curves of light and the number and location of lamps in order to obtain a uniform illumination. Mr. A. A. Wohlauer, Consulting Electrical Engineer, has published a series of valuable papers along these lines in the Electrical World of 1907–08, from which the following pages have been taken.

VALUES OF COS³θ.

θ–Cos³ θ	θ–Cos³ θ	θ–Cos⁴ θ	θ–Cos³ θ
2–.998	21–.813	40–.449	59–.137
3–.995	22–.797	41–.429	60–.125
4–.993	23–.780	42–.410	61–.114
5–.988	24–.762	43–.391	62–.103
6–.983	25–.744	44–.372	63–.0936
7–.978	26–.726	45–.353	64–.0842
8–.971	27–.707	46–.335	65–.0754
9–.963	28–.688	47–.317	66–.0671
10–.955	29–.668	48–.300	67–.0596
11–.945	30–.649	49–.282	68–.0526
12–.935	31–.630	50–.265	69–.0460
13–.925	32–.610	51–.249	70–.0400
14–.914	33–.590	52–.233	71–.0345
15–.901	34–.570	53–.218	72–.0295
16–.888	35–.550	54–.203	73–.0248
17–.874	36–.529	55–.189	74–.0210
18–.860	37–.509	56–.175	75–.0174
19–.845	38–.489	57–.161	76–.0142
20–.829	39–.469	58–.149	77–.0114

We are already familiar with the expression

$$I = \frac{C_p}{h^2} \cos^3 a \qquad (1)$$

where

I = foot-candle illumination on surface
h = perpendicular distance, in feet, from lamp to surface
α = angle between ray and perpendicular
C_p = candle-power in a given direction.

For uniform illumination

$$I = I_0$$

a constant value; and, therefore, the equation of the polar curve or the photometric curve for the light-giving body is

$$C_p = \frac{I_0 h^2}{\cos^3 \alpha} \qquad (2)$$

This gives a curve such as represented in Fig. 111.

Thus it follows that in order to obtain a uniform illumination on a horizontal plane with one lamp, it is necessary that the lamp with or without reflector have a polar curve of the shape represented in Fig. 111.

Heretofore, very little consideration has been paid to these relations in the construction of the lamps or in the design of reflectors. For this reason a coincidence of the above theoretically correct curve with actual lamp curves is merely accidental and is realized only for a small angle. This is apparent from the curves published so far, and, in many instances, the use of the reflector destroys the effect which the lamp itself might have produced.

The area of uniform illumination with one lamp is limited, as it is not practicable to design lamps or reflectors so that their polar curves will follow indefinitely the theoretical curve shown in Fig. 111. At some point the curve has to depart from the theoretical course. It is, therefore, impracticable to illuminate uniformly with a single lamp a greater area than one enclosed by an angle of, say, 25 degrees for incandescent lamps and 50 degrees for arc lamps. We can uniformly illuminate, for instance a table or a desk with one incandescent lamp only when the angle of uniform illumination covers the area of the plane in question.

In order, therefore, to illuminate uniformly larger areas, a number of lamps must be employed and so arranged,

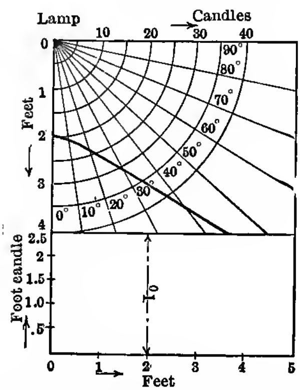


FIG. 111.—Uniform illumination with one lamp.

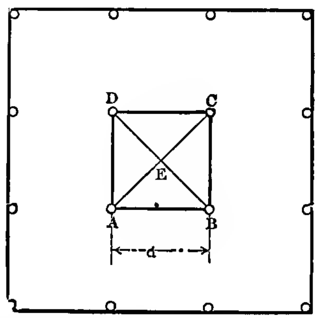


FIG. 112.—Horizontal plane to be uniformly illuminated.

and with polar curves of such a shape, as to produce the desired effect. The problem of these relations is discussed in what follows, and for sake of simplicity light reflected from walls and ceiling is neglected.

The area to be illuminated, for instance, a large square horizontal plane, as shown in Fig. 112, may be divided into a number of squares. At each intersection a lamp is placed at a certain distance above the plane, preferably suspended vertically downward and provided with a reflector. The polar curves of the lamp units will have to be such as to produce a uniform illumination for the whole area.

In order to simplify the matter, at first only the space between two lamps, A and B, will be considered and the conditions studied existing in a vertical plane through two lamp centers along one side of a square (Fig. 112). The problem thus involved is to illuminate uniformly the line $A\ B$ on the plane by the lamps A and B above it.

The simplest way of effecting this is indicated in Fig. 113, where the illumination curve of each lamp has its maximum equal to the desired uniform illumination, I_0, just below the lamp and inclines in a straight line to zero just below the other lamp. It is obvious that such a combination gives a uniform illumination along the line $A\ B$

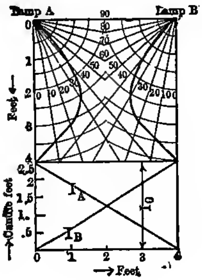


FIG. 113.—Uniform illumination along the line $a\ b$.

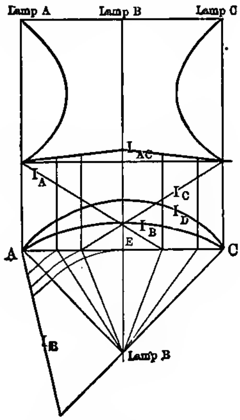


FIG. 114.—Illumination across the diagonal $a\ c$.

If d = distance of lamps,
h = perpendicular distance in feet from lamp to surface height of suspension,
I_0 = desired illumination,
α = angle between ray and perpendicular,
C_p = candle-power in a given direction,

then it can easily be shown that the equation for the illumination curve is

$$I = \frac{I_0}{d} (d - h \tan \alpha) \tag{3}$$

and according to formula (1)

$$I = \frac{C_p}{h^2} \cos^3 \alpha = \frac{I_0}{d} (d - h \tan \alpha)$$

therefore,

$$C_p = \frac{I_0 h^2}{\cos^3 \alpha} \left(\frac{(d - h \tan \alpha)}{d} \right) \qquad (4)$$

the equation for the polar curve of a lamp in the present case.

Such a curve is plotted in Fig. 113 for $h = 4$, $d = 4$, $I_0 = 2.5$, and gives a general idea of the simplest form of a polar curve for uniform illumination of horizontal planes with a number of lamps.

The relation

$$\frac{d}{h} = K$$

is of importance and deserves consideration. For reasons of practicability, as previously mentioned, the area of uniform illumination with one lamp was limited, and similar considerations demand here that the factor K should not exceed values which cannot be realized in practice. Fig. 115 indicates how the polar curves change for different values of K, if I_0 and h are constant. A value of $K = 2$ is hardly practicable, and K having a value of about 1.5 may be considered as the limit of practicability.

In engineering problems of illumination, K may be kept constant and d and h varied in the same ratio. Using then the same polar curve, different intensities of illumination can be obtained; or changing the candle-power of the illuminant the scale of the polar curve must be a different one. However, this may be worked out, it is evident that the two lamp units with such polar curves produce a uniform illumination along the line $A\ B$ between the foot of the perpendiculars of the plane; four of them, A, B, C and D, uniformly illuminate the outline of the square $A\ B\ C\ D$ (Fig. 112).

The point of intersection of the diagonals, E, however, would receive somewhat higher illumination, since the illumination due to one lamp will be at this point

$$\frac{I_E}{4} = 0.2925\, I_0,$$

as can be easily determined. For uniform illumination however, this value should be

$$\frac{I_E}{4} = 0.25\, I_0$$

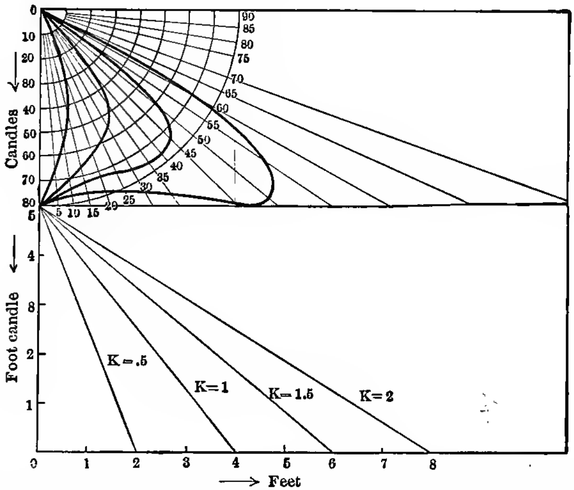


FIG. 115.—Showing polar curves of lamps suspended equally high but at varying distances, yielding the same uniform illumination.

due to the fact that of the total illumination contributed by four lamps, each gives 25 per cent.

The four lamps actually produce an illumination in E

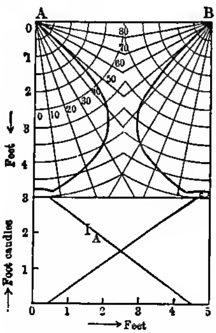
$$I_E = 1.17\, I_0$$

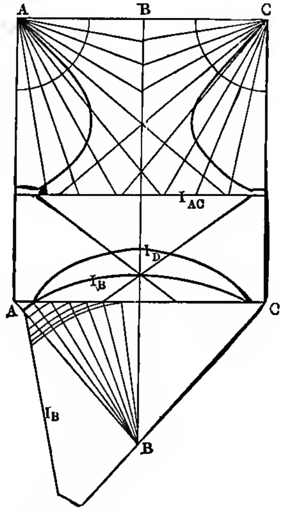
i.e., 17 per cent. more than the desired uniform illumination. The illumination along the diagonal $A\ C$ varies as graphically determined and indicated in Fig. 114. The variation is comparatively small and could be neglected in view of the light reflection from the walls and ceiling.

It is, however, possible to produce a still more uniform illumination, if the illumination curves due to the light of an individual lamp have a shape as indicated, for instance, in Fig. 116.

In some cases, as, for instance, where a room with low ceiling is to be illuminated, and where the available lamps are of too high a candle-power, it may be necessary, in order to obtain the desired illumination, to place the lamps further apart.

The distance, d, between two lamps may then become so great that the light thrown from one lamp towards the other would not illuminate the area below the next lamp if the factor K is kept within the limits of practicability. In such cases the individual lamp alone must yield uniform illumination for an area just below the lamp, or in other words, the polar curve must conform with the law established above and expressed by equation (2) for an angle corresponding to this area. Beyond that angle the illumination curve may practically again be assumed as inclining in a straight line and passing through zero, where the uniform illumination of the next lamp sets in, as indicated in Fig. 116.





FIGS. 116 AND 117.—Perfect uniform illumination along the diagonal.

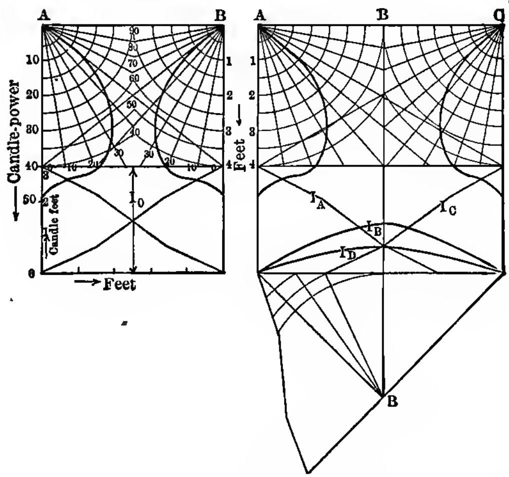
Thus the illumination curve, as well as the polar curve, consists of two parts, the equation of which may be omitted as too complicated for practical use. Such a combination, however, will enable perfect uniform illumination over the whole area.

If we denote

α = the radius of area uniformly illuminated by one lamp,
ϕ = angle for this uniform illumination measured between ray and perpendicular.

then the value

$$\alpha = h \tan \phi$$



FIGS. 118 AND 119.—Another method for uniform illumination.

subject to the same limitations as discussed above for the uniform illumination with one lamp, must be

$$\alpha = 0.085\, d$$

in order to secure the desired illumination I_0 at E, the point of intersection of the diagonals.

This can be easily derived mathematically from Fig. 117, which graphically shows that in such a case the illumination is practically uniform over the whole area. The curves I_b and I_d indicate the light thrown from the lamps B and D on the diagonal A C.

It is beyond the scope of this book to discuss in detail these graphical constructions and mathematical determinations as represented, for instance, in Figs. 114 and 117. They are used here only to assist in the proof of the statements.

There are other means to effect uniform illumination, some of which are indicated in Figs. 118, 119 and 124, they are, however, still more complicated, and their equations rather unhandy for practical use.

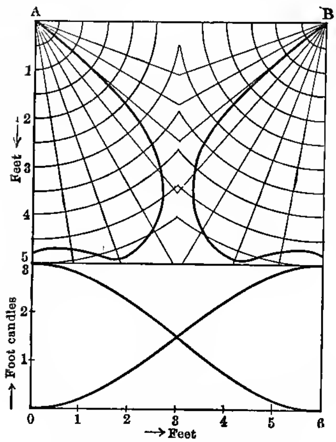


FIG. 120.—General case.

The general case of an illumination curve yielding uniform illumination is represented by Fig. 120, which can be expressed by the equation

$$I = I_0 \frac{(d-x)}{d} + c \sin \frac{4\pi x}{d} \quad (5)$$

where d = distance between two lamps

$x = h \tan \phi$ or distance from lamp abscissa

c = a constant to be determined in every individual case, being equal O, if the illumination curve is a straight line.

Substituting, for equation (2)

$$C_p = k\, I_0$$

where

$$k = \frac{h^2}{\cos^3 \alpha}$$

could be exacted from tables made up for this special purpose, the general equation for a polar curve would be

$$C_p = \frac{I_0\kappa\ (d-x)}{d} + c\kappa \sin \frac{4\pi x}{d} \qquad (6)$$

from which all the possible ways of uniform illumination could be derived.

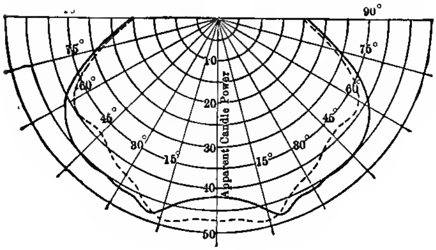
We have demonstrated that in order to illuminate uniformly large horizontal planes a number of lamps must be employed and their light so distributed that the lamps in their combination produce uniform illumination. The different possibilities have been theoretically discussed and a conception has been formed as to the shape of the polar curves.

It now will be interesting and useful to observe to what an extent the theoretical requirements are fulfilled in practice. To this end a number of tests were made by the Electrical Testing Laboratories under Mr. Wohlauer's personal direction.

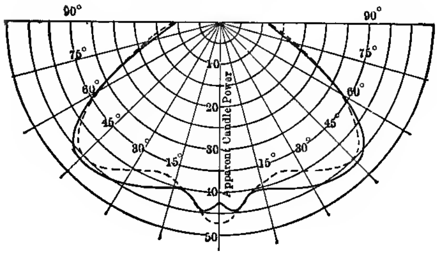
An up-to-date illuminant, a 40-hefner candle "Just" tungsten lamp, was selected and tested under a number of different conditions, as unfrosted, tip frosted and entirely frosted, and in connection with a number of reflectors. The same lamp was used for all the tests, the distance from the photometer kept constant, etc., so that the clearest insight into the prevailing conditions was gained.

A few of the results of the tests are reproduced in Figs. 121 to 123. In Figs. 124 to 126 three of these experimental curves are supplemented by curves obtained from theoretical considerations. The experimental curves are in full line, while the theoretical curves are dotted.

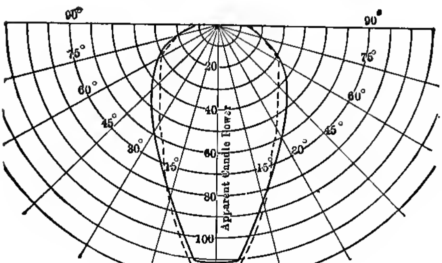
The comparison reveals that it is reasonable to expect that uniform illumination of horizontal planes can be realized in practice, in accordance with the laws derived above. The deviations are slight, the greatest occurring at the upper end, which is due to the fact that the illumination curve of one lamp passes through the zero mark where the maximum illumination of the next lamp sets in. This necessitates that the polar curve must return to zero also. In other words, no light should be emitted in the horizontal



—— Clear Lamp
– – – Partly Frosted
DIFFUSING PRISMATIC REFLECTOR



—— Clear Lamp
—— Tip Frosted
COATED PRISMATIC REFLECTOR



—— Clear Lamp
—— Tip Frosted
CONCENTRATING PRISMATIC REFLECTOR

FIGS. 121, 122 AND 123.—Distribution of light in vertical plane about a 40-watt tungsten lamp backed by holophane prismatic reflectors.

direction, or in the case of incandescent lamps, reflectors must be used so designed that all the light is utilized below the lamp in accordance with the theoretical requirements discussed above. Therefore, if it is desired to illuminate the upper parts of a room, the lamps must be placed at the proper height.

It is interesting to note further that the distance, *d*, between two lamps could be made the same in all three cases which have been selected in order to compare theory with practice. It shows that the same number of lamps are used to illuminate the same area, the variation being

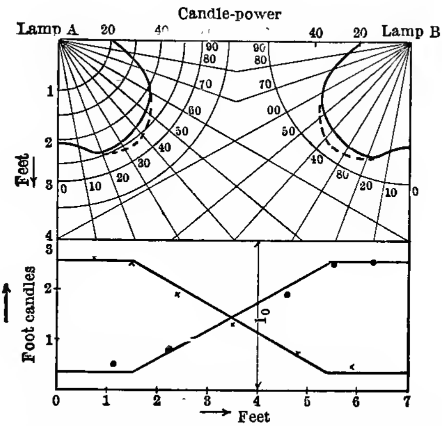
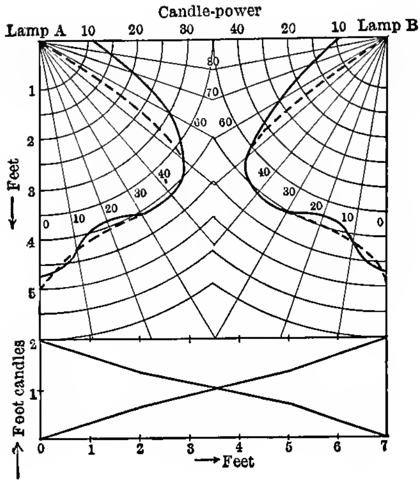
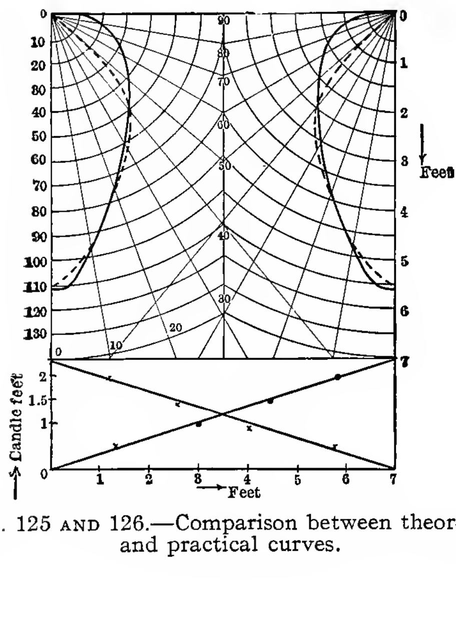


FIG. 124.—Comparison between theoretical and practical curves.

only in the height of the suspension and in the intensity of illumination. Or, in other words, it is possible in practice also, to vary the intensity of uniform illumination by simply changing the reflectors and the height of suspension. It verifies also the recognized fact that the higher the lamp is suspended above the surface, the less the illumination obtained thereon; concentrating reflectors are required for a higher suspension, while for low-ceiling rooms more diffusing reflectors are necessary.

For high suspension—high being a relative term with regard to the candle-power of the lamp—and for concen-





FIGS. 125 AND 126.—Comparison between theoretical and practical curves.

trating reflectors, the illumination curve is always a straight line, while for rooms with low ceilings one often is compelled to introduce the more complicated illumination curves if small lamp units are not available or too expensive in their total cost.

Otherwise the tests show that it is possible to meet the theoretical requirements with the existing sources of light fairly well. This is demonstrated here for the tungsten lamp; a comparison with other lamps, for instance, Nernst lamps with U-shaped filaments and tantalum lamps, etc., would reveal that the conditions are equally promising.

Of course, the reflectors will play the most important part in realizing the theoretical requirements.

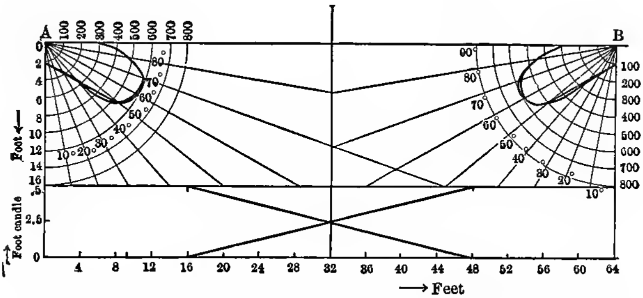


FIG. 127.—Uniform illumination by two enclosed arc lamps.

It will be interesting to call attention to the uniform illumination of very large areas, such as streets, public squares, etc., by arc lamps especially adapted for that purpose. The enclosed arc lamps, for instance, curves of which are shown in Fig. 127, are not very far from realizing the theory in an ideal way. Fig. 127 shows that with the lamps suspended 20 ft. from the ground and placed 64 ft. apart, an almost ideal uniform illumination will be obtained at a height of 4 ft. above the ground.

The area which can be uniformly illuminated by a single source of light of a given mean spherical candle-power depends only on the light emitted and on the illumination required. If

L_s = mean spherical candle-power of lamp,

I_0 = the intensity or uniform illumination in foot-candles,

then the diameter of the circular area illuminated, in feet, is

$$d = 4\sqrt{\frac{L_s}{I_0}} \tag{7}$$

the light absorption by the reflector being temporarily neglected. Equation (7) could be considered as recognizing the absorption by the reflector if L_s is allowed to represent the mean spherical candle-power of the flux actually emitted by the reflector.

Equation (7), which does not contain the height of suspension, shows that the area which can be uniformly illuminated with a certain intensity by a single illuminant of a given mean spherical candle-power does not depend on the height of suspension. By using a proper reflector for each height the light of the illuminant is distributed so that at different heights of suspension the same area is always uniformly illuminated with the same intensity. This relation is illustrated in Fig. 128, where a lamp of a given mean spherical candle-power (L_s = 25 candles) is suspended in one case (A) 5 ft. above the illuminated plane and in another (B) 15 ft., and a uniform illumination of an intensity of I_0 = 3 foot-candles is desired. The reflectors used in the two cases differ, so that in each case the same circular area, 12 ft. in diameter, is uniformly illuminated.

There are, of course, certain practical limits reached in the design of concentrating as well as diffusing reflectors. Without counting extreme cases, the above equation gives the correct value for the diameter of a circular area uniformly illuminated by a single lamp equipped with proper reflector.

Larger areas necessitate a multitude of lamps, and the question arises as to the number of lamps required to illuminate a given area. Theoretically, the number of lamps depends only on the light emitted by each lamp, the intensity of illumination required and the area to be illuminated. If it were possible to so utilize the total flux of a certain number of lamps as to obtain ideal uniform illumination, no restriction would be necessary in practice. However, a single lamp, for instance, will always illuminate only a circular area, and a multitude of lamps, even when skilfully combined, will never lead to an absolutely uniform illumination. This effect can only be

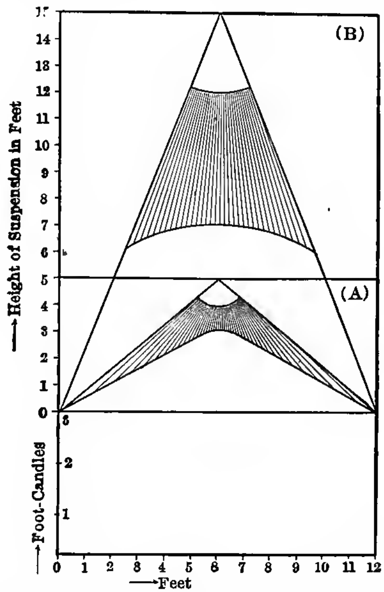


FIG. 128.—Polar candle-power curves for uniform illumination of 3-foot candles by single lamp at different heights of suspension.

approached with more or less accuracy by the various methods of light distribution. Incidentally, the more the illumination approaches the ideal case of uniformity, the better the agreement with the theoretical number of lamps, as indicated below.

It would be possible, for instance, to place lamp units such as discussed above and illustrated by Fig. 128 at an equal height, at a distance D between each other ($D = d =$

diameter of the circular area which can be uniformly illuminated by a single lamp). They would uniformly illuminate tangent circular areas as indicated in Fig. 129. In this case uniform illumination would be obtained along the lines *a b*, *a e*, *e f*, etc., which connect the points of the plane just underneath the centers of the lamp. On the diagonals *a f*, *e b*, etc., however, dark stretches occur, as no light is thrown on the shaded spaces of Fig. 129, which lie outside the boundaries of the uniformly illuminated areas. Such uniform illumination, with intermediate dark spots, would be permissible in places where (as in restaurants and the like) the tables or the objects to be illuminated could be so located as to be just within the

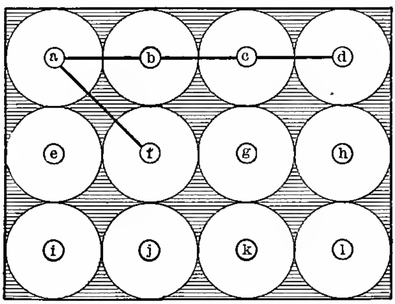


FIG. 129.—Sporadical uniform illumination.

limits of uniform illumination, while the dark spots fall in places which do not require the full share of illumination. For office buildings, auditoriums, department stores and the like, such an illumination would not be satisfactory, as it is not possible to predetermine the exact position of the objects to be illuminated, and non-illuminated spaces might prove very annoying.

If the light distribution of the lamps be so changed that the corresponding illumination curves are inclining and overlap each other, no dark spaces will be encountered and the unevenness will be kept down to a minimum. There will be points of maximum illumination; the non-uniformity, however, will be very slight and can be neglected in practice or overcome by certain modifications in the light distribution. (See Fig. 131.)

The distance between the lamps could then be calculated from the formula

$$D = K\sqrt{\frac{L_v}{I_0}} \tag{8}$$

where

$$K = \frac{D}{H}$$

L_v = candle-power of the lamp vertically, downward.
I_0 = intensity of illumination in foot-candles,
H = minimum height of suspension, in feet.

Equation (8), which is generally applicable in all cases, could be used also instead of equation (7), as can readily be recognized and demonstrated. There is a certain relation between L_v, K and L_s, the latter being the mean spherical candle-power of a lamp, as stated above, which can be expressed by the equation

$$K = \sqrt{\frac{\alpha\, L_s}{L_v}} \tag{9}$$

where α is a constant factor which depends on the method of light distribution and varies from 8 to 16, according to the shape of the polar candle-power curve of each lamp and to the location of the lamps. For instance $K = \sqrt{\frac{16\, L_s}{L_v}}$ for the method of illumination represented by Figs. 128 and 129 and $K = \sqrt{\frac{8 L_s}{L_v}}$ for the method illustrated by Fig. 130, and $K = \sqrt{\frac{9.7\, L_s}{L_v}}$ for the modification corresponding to the polar candle-power curve, as indicated by Fig. 131.

It is possible, however, to start directly from an equation for the distance between the lamps, which would have the general form,

$$D = \sqrt{\frac{\alpha L_s}{I_0}} \tag{10}$$

wherein α has the same values as mentioned above. Equation (10) leads to the formulas $D = \sqrt{\frac{16L_s}{I_0}}$ for "horizontal" illumination curves, $D = \sqrt{\frac{8 L_s}{I_0}}$ for "straight inclining" illumination curves and $D = \sqrt{\frac{9.7L_s}{I_0}}$ for the modification.

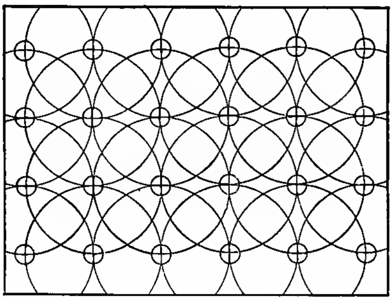


FIG. 130.—Uniform illumination by overlapping straight illumination curves.

Having determined the distance between the lamps, one can find the number of lamps required for the illumination of a certain area, S. Since $N = \frac{S}{D^2}$ the general form of the equation for determining the number of lamps will be,

$$N = \frac{SI_0}{\alpha L_s} \tag{11}$$

Equation (11) enables one to ascertain the number of lamps of a certain mean spherical candle-power to illuminate a certain area with a chosen intensity of illumination.

It will be recognized as a fundamental formula which can be used by the illuminating engineer in numerous cases.

It is obvious that, if there is no light absorption and the illumination is uniform, the number of lamps required would be

$$N = \frac{SI_0}{4\pi L_s} \tag{12}$$

which shows that the comparison of α with 4π, is a criterion for the uniformity of illumination as well as for the "efficiency" of the reflector. It is seen, furthermore, that if α equal 16, the uniform illumination cannot be complete, a conclusion indicating the dark spots discussed above and illustrated in Fig. 129. It is also evident that for a value of α of 9.7 corresponding to the modification illustrated in Fig. 131, the uniformity of illumination is much better.

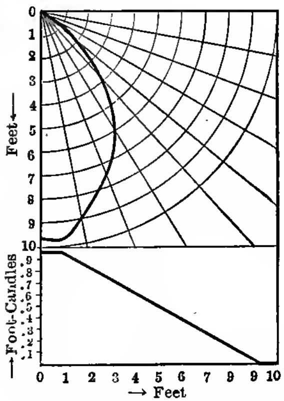


FIG. 131.—Modification of illumination curves.

For practical calculations the factor α, which might be termed "constant of the reflector," must depend upon the loss of light due to the absorption in the reflector, a consideration which will modify the above theoretical values of α according to the "efficiency" of the reflector.

Equation (11) is correct only for methods of light distribution as discussed above, which are theoretical, at least up to the present time. However, it has a practical value in connection with existing reflectors and methods of light distribution if the proper value of α is introduced into the calculations. This value can be determined either experimentally or mathematically. Mr. Wohlauer has attempted to ascertain the value of α for the various commercial reflectors utilizing data gathered together from trade publications. The results given in the accompanying table may convey a fair idea of the constants of the various reflectors.

VALUES OF THE CONSTANT α FOR VARIOUS REFLECTORS AND LAMP DISTRIBUTIONS.

Holophane reflector. Form C	4.3
Holophane reflector. From D or S	5.
Holophane Pagoda reflector. No. 2510	8.
" Straight inclining " illumination curves	8.
Holophane bowl reflector. Form B	6.
Modification of " straight lines " illumination	9.7
National X-Ray reflector. No. 700	10.
Ideal uniform illumination. (4π)	12.5
" Sporadical " uniform illumination	16.

It should be stated that in the case of the practical and commercial reflectors, the values of α given in the table are fully correct only when the number of lamps utilized for illumination is rather high, so that all of the lamps participate in the illumination of the various points of the plane. For a very small number of lamps, the above values of α will not lead to such correct results, although the deviations are not very great. If, however, the polar candle-power curves of the lamps have the theoretical shape assumed above, so that one lamp does not throw its light beyond the foot of the next lamp, a much greater accuracy will be obtained.

It has been pointed out by E. W. Weinbeer that for every type of lamp or for the corresponding polar-curve a certain height of suspension can be calculated as the minimum allowable for uniform illumination. He stated that the lamp units can be raised above the minimum height without impairing the intensity of illumination or the uniformity of light distribution. However, a suspension lower than the minimum will result in non-uniform illumination if the distances between the lamps and the shape of the polar-curve remain the same.

The facts stated by Weinbeer are applicable to these theoretical curves, which represent the case of minimum height of suspension, corresponding to a certain value of K.

A suspension lower than H without a change of the other values, as K, D, polar-curves, etc., results in non-uniform illumination, as illustrated by Figs. 113 and 132. In Fig. 113, where $H = 4$, $D = 4$, the illumination I_{ab} is uniform, while in Fig. 132, where the suspension is 1 ft. lower, the variable illumination curve I_{ab} will be obtained. This is due to the fact that the illumination curve of a single lamp passes through zero at the points S and T (of Fig. 132), where the illumination of the other lamp has not yet reached its maximum value equal to the desired uniform illumination.

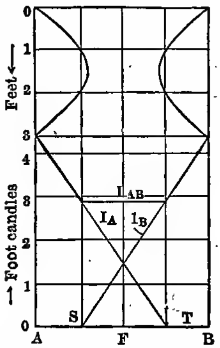


FIG. 132.—Non-uniform illumination, lower suspension.

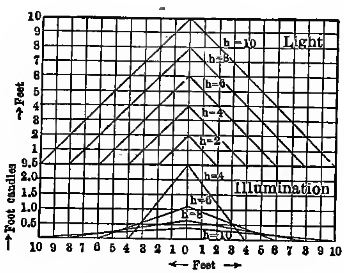


FIG. 133.—Influence of height of suspension upon intensity and uniformity of illumination from one lamp.

On the other hand, an increase of the height of suspension above H changes neither the intensity of the source nor the uniformity of illumination, provided again that the other factors, such as distance, polar-curves, etc., remain unchanged.

This may be considered as an important law of illuminating engineering, and it is, therefore, pertinent to thoroughly investigate it in order to bring about its clear understanding.

It is well to start with the illumination produced by a single lamp and to remember that the illumination of a single lamp decreases proportionally to the square of the height of suspension, as illustrated by curve $R\,S\,T$ of

Fig. 134 and by table following. The uniformity becomes better with increase height of suspension, or, in other words, the relation between maximum and minimum illumination decreases toward unity. (Fig. 133).

INTENSITIES OF HORIZONTAL ILLUMINATION FROM ONE LAMP

Height, feet	2	3	4	5	6	7	8	9	10
Illumination below lamps.	10	4.44	2.5	1.6	1.11	0.82	0.625	0.494	0.4

If (not more than) two lamps are employed, and if the polar-curves have a shape as suggested above, the following conditions will prevail. The line between the points A and B (the foot of the perpendiculars from the lamp centers) will be uniformly illuminated if the height of suspension is such that the illumination curve of one lamp passes through zero just where the maximum illumination of the next lamp sets in.

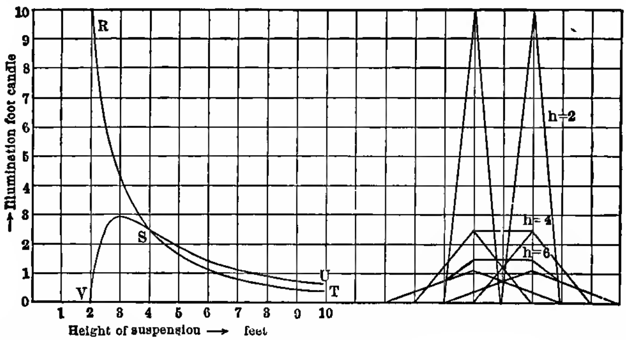


FIG. 134.—Influence of height of suspension upon illumination due to two lamps.

If the height of suspension is smaller, the illumination will not be uniform, as illustrated in Fig. 132, the illumination of the point F, which is just in the center of the line A B, will vary according to curve V S of Fig. 134, while the illumination in the points just below the lamps is the same as if one lamp alone were present, which is illustrated by curve R S, in Fig. 134. S is the minimum height of suspension.

INTENSITIES OF HORIZONTAL ILLUMINATION FROM TWO LAMPS.

Height, feet	Foot-candle illumination	
	Below lamps	Between lamps
2	10	0
2.25	7.8	1.66
2.5	6.4	2.56
3	4.4	2.96
3.5	3.25	2.8
4	2.5	2.5
5	1.92	1.92
6	1.48	1.48
7	1.16	1.16
8	0.94	0.94
9	0.77	0.77
10	0.64	0.64

If the lamp is suspended higher than the limit for uniform illumination, the light distribution will remain uniform along the line *A B*, but it will decrease with the height of suspension, although not proportional to the square of the height of suspension. This is illustrated by the curve *S U* of Fig. 134 which gives the illumination for the points *A* and *B*, as well as for the point *F*. and shows that the illumination is practically the same for all three points. The values of this curve and of the table above are calculated by means of the following formulas:

$$I_A = \frac{L}{h^2} + \frac{L}{h^2}\left(1 - \frac{H}{h}\right) \tag{13}$$

$$I_F = \frac{L}{h^2}\left(2 - \frac{H}{h}\right) \tag{14}$$

in which

L = candle-power illumination vertically downward.
h = variable distance in feet from lamp to surface.
H = height in feet of suspension for uniform illumination.
I = foot-candle illumination.

(Index *A* or *F* in the tables refer to the corresponding point on the surface.)

In equation (13) the quantity $\frac{L}{h^2}\left(1-\frac{H}{h}\right)$ reduces to zero for $h < H$.

If $h > H$, equations (13) and (14) are identical, which proves that the illumination I_{ab} is uniform for h larger than H.

The illumination of the space outside of the line $A\ B$ will not be discussed.

If a multitude of lamps is employed to illuminate a certain area, the illumination will be practically uniform if the conditions comply with the laws deduced above. A suspension of the lamps lower than corresponding to the above laws results in non-uniform illumination, as stated. There is no difference if one, two or more lamps are employed

For higher suspension than "minimum height of suspension," equations can be deduced from which the values of illumination for different heights of suspension can be calculated. These equations are extremely long and are rather complex for the general case, but they will be considerably reduced and simplified if the relation $\frac{h}{H}$ does not exceed practical values.

From such equations, the values of illumination for different points have been calculated, also graphical determinations have been employed, and it has been found that the number of lamps which participate in the illumination of a certain point increases with the height of suspension, and while the illumination due to a single lamp decreases proportionally to the square of the height of suspension, the total illumination remains the same, however, much the lamps are raised above the surface.

Equations (15) and (16) have been used to calculate the illumination for the point A, just below the lamp and for E, the point of intersection of the diagonals. These equations consist of a number of members indicating the number of lamps which participate in the illumination of the point in question. For instance, in equation (15), the first member $\frac{L}{h^2}$ gives the illumination produced by the lamp just above the point A. The next member $\frac{L}{h^2}\left(1.1 - 1.2\,\frac{H}{h}\right)$ represents the illumination from the lamps nearest to lamp A, the next following member, the illumination from the next set of lamps, etc. The number of these members, as said, increases with the height of suspension, while a member is zero as long as the expression in parentheses remains zero or less than that value.

$$\left.\begin{aligned} I_A = \frac{L_v}{h^2} &+ \frac{4L_v}{h^2}\left(1.1 - 1.2\,\frac{H}{h}\right) \\ &+ \frac{4L_v}{h^2}\left(1.1 - 1.7\,\frac{H}{h}\right) \\ &+ \frac{4L_v}{h^2}\left(1.1 - 2.4\,\frac{H}{h}\right) \\ &+ \frac{4L_v}{h^2}\left(1.1 - 3.4\,\frac{H}{h}\right) \\ &+ \frac{8L_v}{h^2}\left(1.1 - 2.7\,\frac{H}{h}\right) + \text{etc.} \end{aligned}\right\} \quad (15)$$

$$\left.\begin{aligned} I_E = &\frac{4L_v}{h^2}\left(1.1 - .85\frac{H}{h}\right) + \\ &\frac{4L_v}{h^2}\left(1.1 - 2.55\frac{H}{h}\right) + \\ &\frac{8L_v}{h^2}\left(1.1 - 1.9\,\frac{H}{h}\right) + \\ &\frac{8L_v}{h^2}\left(1.1 - 3.06\frac{H}{h}\right) + \\ &\frac{8L_v}{h^2}\left(1.1 - 3.34\frac{H}{h}\right) + \text{etc.} \end{aligned}\right\} \quad (16)$$

The equations (15) and (16) are based on a distribution of light such as is represented by Fig. 116; as shown in Figs. 116 and 117 this distribution provides practically uniform illumination over the whole area at the minimum height of suspension.

The illumination under a certain lamp, which comes from this lamp, is uniform for an area within a circle, the radius of which is .085 times the distance between two lamps, and beyond this area the illumination from this lamp decreases regularly to zero at a point where the maximum illumination of the next lamp begins.

As an example, the equations have been used for the

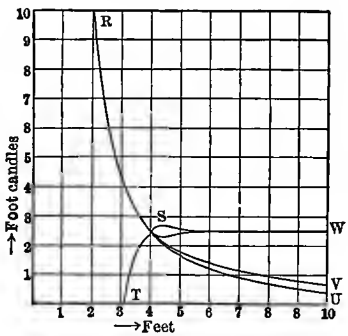


FIG. 135.—Illumination by a multitude of lamps.

calculation of the intensities of illumination at different heights of suspension introducing into the equations as constants the values, $D = 4$ ft., $H = 4$ ft., and $L_v = 40$ candles.

The results of the calculations are represented in Fig. 135, and the following table. S illustrates again the conditions for minimum height of suspension; the curves $R\,S$ and $S\,T$ refer to lower suspension, $R\,S$ giving the illumination just below the lamps, $T\,S$ the illumination at the point of intersection of the diagonals. The line $S\,W$, however, shows the illumination for suspensions higher than the minimum and proves that the illumination remains practically constant and uniform if the lamps are raised above the minimum height of suspension.

INTENSITIES OF ILLUMINATION FROM A MULTITUDE OF LAMPS.

Height, feet	Foot-candle illumination	
	Below lamps	At intersection of diagonals
2	10	0
2.25	7.8	0
2.5	6.4	0
3	4.4	0
3.5	3.25	1.75
4	2.5	2.5
4.5	2.35	2.65
5	2.45	2.55
6	2.48	2.53
7	2.49	2.51
8	2.5	2.5
9	2.5	2.5
10	2.5	2.5

This law might be derived more systematically by an extensive use of mathematics. It is believed, however, that the above method is rather desirable, as the facts are brought out in a more comprehensive form.

From the above law it is permissible to draw the following conclusion, which is also of importance for illuminating engineering: It is not necessary to make the distance D between two lamps less than the minimum height of suspension H; in other words, the factor K need not be smaller than 1.

For example, if the plane should be illuminated with an intensity of three foot-candles and, for instance, lamps having a candle-power of 75 candles vertically downward are available, the minimum height of suspension would be

$H = \sqrt{\frac{L_v}{I}} = \sqrt{\frac{75}{3}} = 5$, and, therefore, the distance between

the lamps also = 5 for polar curves of $K = 1$ and larger than that for greater values of K. If it is necessary for reasons of practicability, æsthetics, etc., to suspend the lamps higher than 5 ft., one may do so without impairing the intensity of illumination or the uniformity of light distribution, but it is not necessary to change the polar-curve into one of which K is less than 1.

It is even better to suspend the lamps above their minimum height of suspension since, as shown in the above discussion, the uniformity of illumination is improved by increasing the height of suspension.

APPENDIX A.

The following table gives the current-carrying capacities of the respective sizes of copper wire with rubber and weather-proof insulation as approved by the National Board of Fire Underwriters.

B. & S. gage	Circular mils	Amperes rubber covered	Amperes weather proof
18	1,624	3	5
16	2,583	6	8
14	4,107	12	16
12	6,530	17	23
10	10,380	24	32
8	16,510	33	46
6	26,250	46	65
5	33,100	54	77
4	41,740	65	92
3	52,630	76	110
2	66,370	90	131
1	63,690	107	156
0	105,500	127	185
00	133,100	150	220
000	167,800	177	262
0000	211,600	210	312

The question of potential drop is not considered in the above tables.

No wire smaller than No. 14 is used except for fixture work and flexible cords.

In computing the size of wire to be used for lighting circuits, the following formula will be of service:

$$A = \frac{I \times l \times K}{e}$$

where A equals the area of the wire in circular mils,
e equals the permissible drop in volts,
I equals the current on the line in amperes,
l equals the distance from the mains to the center of distribution or outlet in feet, and
K equals 21.62 for direct-current circuits.
K equals 24.00 for lighting load on single-phase alternating current circuits.
K equals 26.60 for lighting and power loads on single-phase alternating current circuits.
K equals 12.00 for lighting load on two-phase, four-wire, and on three-phase, three-wire, alternating-current circuits.
K equals 13.30 for lighting and power load on two-phase, four-wire, and three-phase, three-wire, alternating-current circuits.

INDEX.